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## THESIS

**GENERATION OF GLOBAL SYSTEM FOR MOBILE  
(GSM) SIGNALS AND THEIR TIME DIFFERENCE OF  
ARRIVAL (TDOA) ESTIMATION**

by

Timothy N. Haney

June 2000

Thesis Advisor:  
Co-Advisor:

Ralph Hippenstiel  
Tri Ha

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(TDOA) ESTIMATION**

Timothy N. Haney  
Lieutenant, United States Navy  
B.S., Southern University, 1994

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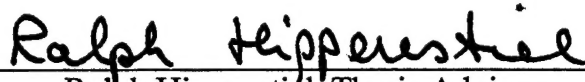
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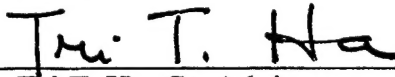
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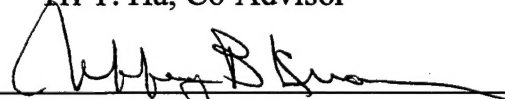
Author:

  
Timothy N. Haney

Approved by:

  
Ralph Hippenstiel, Thesis Advisor

  
Tri T. Ha, Co-Advisor

  
Jeffrey B. Knorr, Chairman

Department of Electrical and Computer Engineering



## **ABSTRACT**

Emitter localization is a very important communications tool that will be extremely valuable to a multitude of different military as well as civilian applications. In many parts of the world, GSM is the preferred method of modulation used in mobile phone traffic. This thesis addresses the time difference of arrival estimation applied to GSM type signals using wavelet-based techniques. Signals are generated using the Hewlett-Packard Advanced Design System software and processed using algorithms based on Matlab. The results of this thesis prove that we can improve upon the localization of a GSM emitter through the use of wavelet-based denoising techniques.



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## **I. INTRODUCTION**

### **A. BACKGROUND**

The ability to obtain localization information from a cellular phone transmission is increasingly becoming a much sought-after facility. Thanks to some improved techniques in cellular communications, this ability is very much realizable. As a matter of fact, recently there has been legislation which requires the development of this technology. When a 911 call is made from a wire line phone, the dispatcher automatically can provide the location of where the call was made. Currently, there is no such capability for calls made from cellular phones. In October 1999, President Clinton signed a law which makes 911 the official nationwide emergency number for both regular and cellular phones [Appendix A]. This legislation followed a move by the FCC which requires, by the end of 2001, that cellular 911 calls automatically provide the caller's location [Appendix A].

There are countless ways in which the development of this technology will be beneficial to many different public and private enterprises. If this technology is utilized to its full potential, it will completely change the way the entire wireless industry does business as well provide an invaluable resource for many military applications. Listed here are just a few of the benefits:

- Location Sensitive Billing – Network operators will be able apply charges depending on the location of the mobile. In this way, different rates can be charged for calls from the home or office. This would allow network

operators without copper-based public switched telephone network (PSTN) to offer competitive rates for calls from the home or office.[1]

- Intelligent Transport Systems – Traffic congestion can be determined by the number of cellular calls coming from a particular stretch of highway. Vehicles with installed maps can provide directions and alternate routes to travelers to avoid congestion and traffic mishaps. Also companies could track the location of all the vehicles in its fleet and more efficiently dispatch vehicles according to the traffic situation and distance to the final destination.
- Enhanced Network Performance – By monitoring the frequency of calls from various locations over time, cellular networks can be better organized to provide the optimum service for a particular coverage area. This includes the ability to accurately monitor the movement of the mobile telephone to enable the network to make better decisions on when to initiate call handoff to a different cell.
- Electronic Surveillance – Law enforcement authorities can use position information to track the location of a mobile station which could serve a multitude of purposes.[2]
- Automobile Security – Location information can be gained from a strategically placed mobile transmitter in the event of a car theft. This would aid tremendously to the recovery of stolen vehicles and greater rate of apprehension of car thieves.

- Unauthorized Cellular Usage Detection – Cellular carriers have long been plagued by the unauthorized access to personal communications systems . These illegal activities would diminish drastically with the advent of cellular phone localization.

## **B. OBJECTIVE**

There are several methods available that would allow us to implement a position location capability into cellular communications systems. For reasons that will become more apparent in the following chapters, the Time Difference of Arrival (TDOA) method appears to be the most logical choice. In this thesis, we will discuss the TDOA estimation and its application to Global System for Mobile (GSM) signals. Specifically, we will investigate several methods to reduce the mean squared error of the TDOA estimate, thereby allowing a position localization with a corresponding lower error probability.

GSM was chosen to provide the backbone for this research because of its worldwide acceptance as the Personal Communication Service (PCS) network of choice and its inherent positioning localization advantages. We will discuss this system in great detail in order to provide an understanding of its advantages. We will also demonstrate our ability to simulate GSM signals using the Hewlett-Packard Advanced Design System (HP-ADS) program. Finally, these generated GSM signals will be evaluated using Matlab-based programs to provide an indication of how to improve upon the localization of a GSM emitter.

### **C. RELATED WORK**

The initial research on this project was begun in 1998 by Unal Aktas, LTJG, Turkish Navy. His work focused on the use of the wavelet transform to increase the accuracy of the TDOA estimation. He investigated several different denoising techniques and presented a comparison of the techniques. These included wavelet denoising based on Donoho's method, wavelet denoising using the Wo-So-Ching threshold, wavelet denoising using hyperbolic shrinkage, wavelet denoising using median filtering, modified approximate maximum-likelihood delay estimation, denoising based on the fourth order moment, and a time-varying approximate maximum-likelihood technique. The results of his work showed that the fourth order moment, and the modified approximate maximum-likelihood techniques were superior to the others. For that reason, this thesis only makes use of those three techniques. Modified versions of the Matlab code for wavelet-based denoising developed by Aktas, are used in this thesis.

## **II. GSM AND THE TIME DIFFERENCE OF ARRIVAL**

### **A. REVIEW OF GSM**

Global System for Mobile Communications (GSM) is the European standard for digital mobile telephones. It was developed in 1990 and first implemented in 1991 to replace first generation European cellular systems, which were generally incompatible with each other. It has gained worldwide acceptance as the first universal digital cellular system with modern network features extended to each mobile user, and is a strong contender for Personal Communication Service (PCS) above 1800 MHz throughout the world. [3]

#### **1. GSM Channel Structure**

One characteristic of GSM that makes it so desirable is that it uses both Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) to transmit and receive information. TDMA allows for multiple conversations to take place simultaneously at the same frequency (channel) by rationing different time slots to each user. GSM uses two 25 MHz bands of the radio frequency spectrum, one for uplink (mobile station to base station) and the other for downlink (base station to mobile). FDMA divides each of these blocks into 125 channels, each with a bandwidth of 200 kHz. TDMA allows for 8 different time slots, as shown in Figure 2.1 from Ref [1], with each time slot being 576.92 microseconds in duration. The grouping of these 8 time slots is called a frame. This combined with the mechanics of FDMA provides for a total

of 1000 actual speech or data channels. Currently, there is a half-rate speech coder in the process of development that will double the number of channels to 2000 [4].

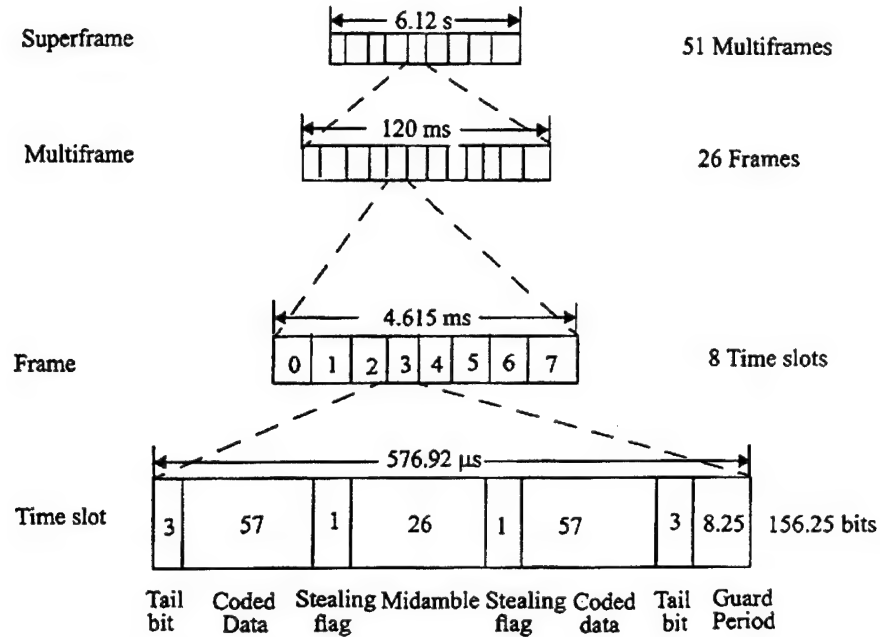


Figure 2.1: GSM Frame Structure

Of the total number of available channels, a certain number of them are dedicated as control channels or logical channels. Each logical channel has a specific purpose ranging from transmitting system parameters, to coordinating channel usage between base station and mobile. The logical channels are mapped onto dedicated time slots of particular frames. This is executed using a burst structure, the most commonly used being a normal burst. Contained in the middle of this burst is a 26-bit training sequence, chosen for its correlation properties. This received burst is correlated with a local copy of the training sequence to allow for the estimation of the impulse response of the radio channel, which aids in the demodulation of the bits in the burst. Another important characteristic of training sequences in the different burst structures of GSM is that they



lend themselves to the measurement of time which can be used to aid in the gathering of time-based positioning information [1].

## 2. GMSK

GSM uses 0.3 Gaussian Minimum Shift Keying (GMSK) as its method of modulation. This facilitates the use of narrow bandwidth and coherent detection capability. In GMSK, the rectangular pulses are passed through a Gaussian filter prior to their passing through a modulator. Within this filter, baseband Gaussian pulse shaping smoothes the phase trajectory of the MSK signal, and thus stabilizes the instantaneous frequency variations over time. The result of this is significantly reduced sidelobe levels in the transmitted spectrum. The value 0.3 represents the 3 dB-bandwidth-bit duration product (BT) or normalized pre-Gaussian bandwidth, which corresponds to a filter bandwidth of 81.25 kHz for an aggregate data rate of 270.8 Kbps. As shown in Figure 2.2 from Ref. [4], sidelobe levels fall off dramatically with decreasing BT product. However, reducing the BT product increases the irreducible error rate which is a product of intersymbol interference (ISI) created in the Gaussian filtering process. GMSK sacrifices the irreducible error rate for extremely good spectral efficiency and constant envelope properties. This is a good tradeoff as long as the irreducible error rate is less than that produced by the mobile channel.

All base stations transmit a GSM synchronization burst on the synchronization channel. Contained in the burst is another useful 64-bit training sequence. The autocorrelation function for this sequence reveals a main correlation peak with a width of 4 bits. Compared to signals used in other time-based positioning systems, this is

relatively wide. The GMSK modulation technique is responsible for this increased width. This is significant from a time-based positioning standpoint because it reduces the timing resolution and hence the maximum achievable position accuracy.

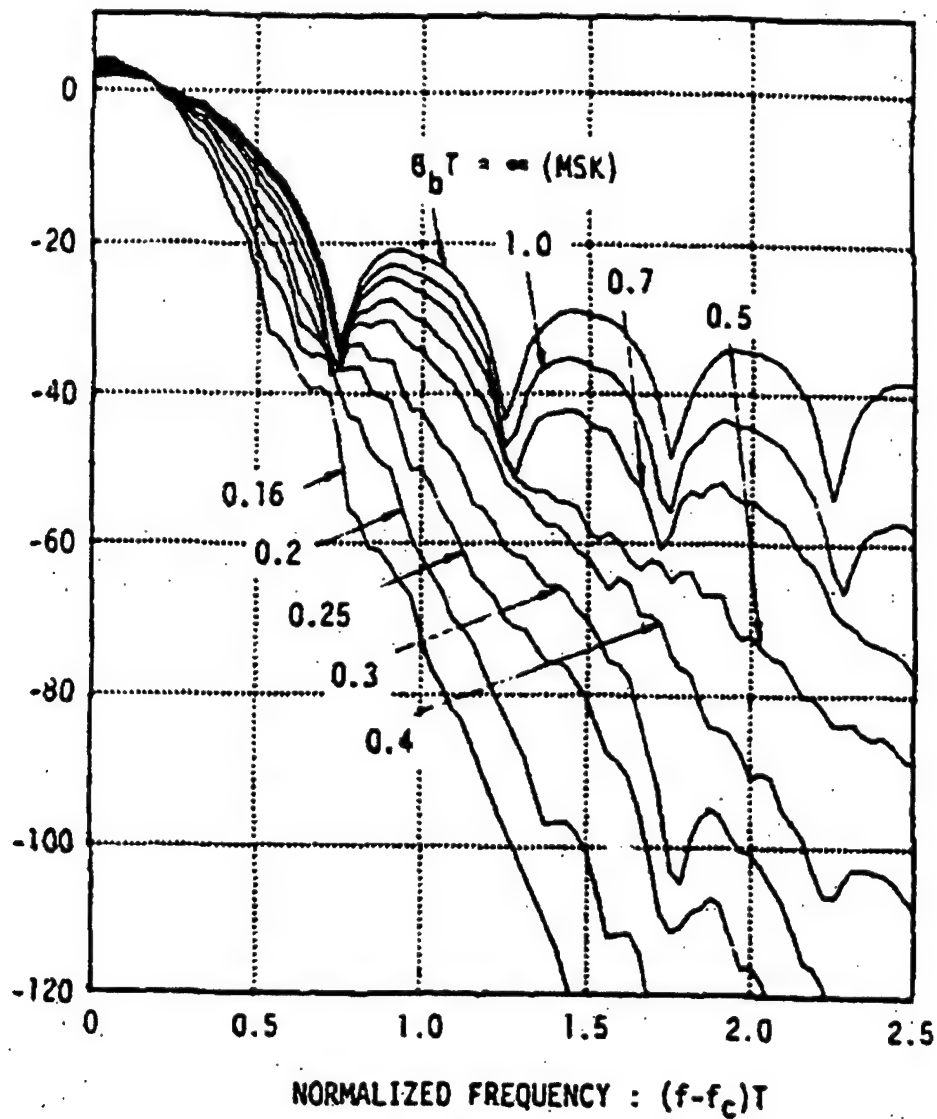


Figure 2.2: Power Spectral Density of a GMSK Signal

### **3. Interference**

In the mobile radio path, the GSM signal will experience some ISI. The mobile radio channel is generally hostile in nature and can affect the signal to such an extent that the system performance is seriously degraded [5]. Inherent in any communication system is the phenomenon known as multipath. This refers to the situation where a signal propagating from a transmitter to a receiver can travel via several different paths including line of sight and one or more reflected paths. The reflected paths cause delay, attenuation in the amplitude, and phase shifts relative to the direct path. In some environments, multipath components may be delayed by up to 30 microseconds. These delayed components cause ISI in the received signal. [6] An example of this interference is illustrated in Figure 2.3 from Ref. [1]. As shown, it is a distorted correlation peak which can cause errors in any time measurements. The degree of distortion depends on the relative amplitude, delay, and phase of the received signals.

The conventional GSM receiver contains a signal demodulator which equalizes the received signal to improve system performance in the presence of multipath by combining the information received from the different arrivals. This process is called adaptive equalization. The equalizer does not reject multipath signals, but combines them. However, for positioning reasons, the receiver needs to be able to determine the first arrival corresponding to the line of sight, and thus requires a multipath rejection algorithm [1].

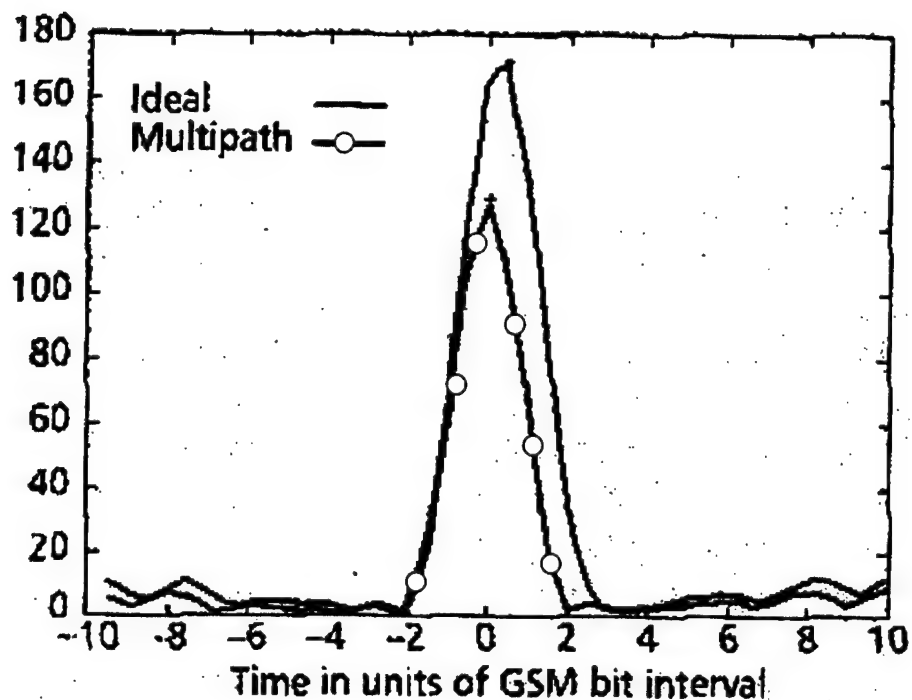


Figure 2.3: Comparison of Ideal and Multipath Distorted Correlation Functions for GSM Synchronization Burst (64-Bit Training Sequence)

#### 4. GSM Coverage Area Layout

The area that a GSM network covers is divided into a number of cells, each served by its own base station (BS), also known as a base transceiver station. The number of cells served by each BS, called a cluster, is determined by the amount of system capacity (total available channels) required for a particular area. A larger cluster size is an indication of a larger capacity system. One tradeoff associated with the larger capacity system is that a more complex system is required to control the increased demand for frequency reuse. Also, more cells per cluster translates into smaller

individual cell size and thus, more co-channel interference for which to account, as well as a greater frequency of handoffs between cells. The typical cluster size is 4, 7, or 12.

Each cell is distinguished by a unique cell identifier and is allocated one or more uplink/downlink frequency pairs. Multiple BS's may be grouped together under the control of a base station controller (BSC). In turn, several BSC's are usually controlled by a mobile service center (MSC), which handles tasks such as call routing and serves as the interface between the mobile network and the fixed telephone network.

## **5. GSM Performance Enhancing Techniques**

In addition to increasing the number of cells per cluster, GSM uses a number of other methods to increase capacity. These are important because they provide favorable implications for positioning. One such technique is the use of sectorized cells. Sectoring effectively breaks the cell down into groups of frequencies (channels) that are only used within a particular region. This is best exemplified as slicing a pie into equal segments. Not only does this technique offer additional information for use by a positioning system, but it also has the effect of reducing co-channel interference. This reduced co-channel interference is due to the fact that a given cell receives interference and transmits with only a fraction of the available co-channel cells.

Another performance enhancing technique employed by GSM is slow frequency hopping; so termed because the hopping rate is low compared with the symbol or bit rate. The mobile radio channel is a frequency-selective fading channel, which means the propagation conditions are different for each individual radio frequency. Slow-frequency hopping is used instead of fast-frequency hopping because, in order to perform well, a

frequency synthesizer must be able to change its frequency and settle quietly on a new one within a fraction of one time slot (576.92 microseconds). Frequency hopping provides frequency diversity to overcome Rayleigh fading due to the multipath propagation environment. Frequency hopping also provides interference diversity. The amount of interference varies with any given channel within any given cell. A receiver set to a channel with strong interference will suffer excessive errors over long strings of bursts. Frequency hopping prevents the receiver from spending successive bursts on the same high-interference channel. These beneficial effects of frequency hopping contribute to a reduction in the minimum signal-to-noise ratio (SNR) required for good communications.

## **B. POSITIONING TECHNIQUES**

It is important to remember that in order to comply with the FCC ruling, any positioning solution must work with existing phones. For this reason, most cellular geolocation proposals are multilateral, where the estimate of the mobile's position is formed by a network rather than by the mobile itself. Hence, the unilateral proposal of adding a global positioning system (GPS) capability to mobile phones is not a universal solution since mobile telephone operators would have to replace or retrofit every mobile telephone. Even if it were feasible to carry out this retrofit, there are other factors that would make this a futile attempt. First of all, the size and cost of mobile transmitters would be considerably increased because of the incorporated GPS receiver. Moreover, a clear view of the sky is necessary to receive usable GPS data from at least three satellites,

which makes the system useless in areas surrounded by buildings, mountains, and other obstructions—common working environments for cellular communications.[7]

There are three ways that position localization information can be determined using the signaling aspects inherent in the GSM specification. One is through the Angle of Arrival (AOA) method, which uses sector information. Second, is through the use of propagation time using timing advances (TA). Third, is the Time Difference of Arrival (TDOA) method, which offers several advantages over the previous methods. In addition to providing some immunity against timing errors when the source of major reflections is near the mobile, the TDOA method is less expensive to put in place than the AOA method. Also, the AOA and TOA methods are hampered by requirements for line of sight (LOS) signal components, whereas the TDOA method may work accurately without a LOS component [8]. Each method will be briefly described before taking an in-depth look at the TDOA

### **1. Angle of Arrival (AOA)**

If two or more BS platforms are used, the location of the desired mobile in two dimensions can be determined from the intersection of two or more lines of bearing (LOB), with each LOB being formed by a radial from a base station to the mobile. Figure 2.4 illustrates the method known as triangulation using three different platforms. Here, the LOB's from the mobile to two adjacent platforms form what is called a measured angle,  $\phi$ . After two measured angles are calculated, trigonometry or analytic geometry may then be used to deduce the location of the MS.

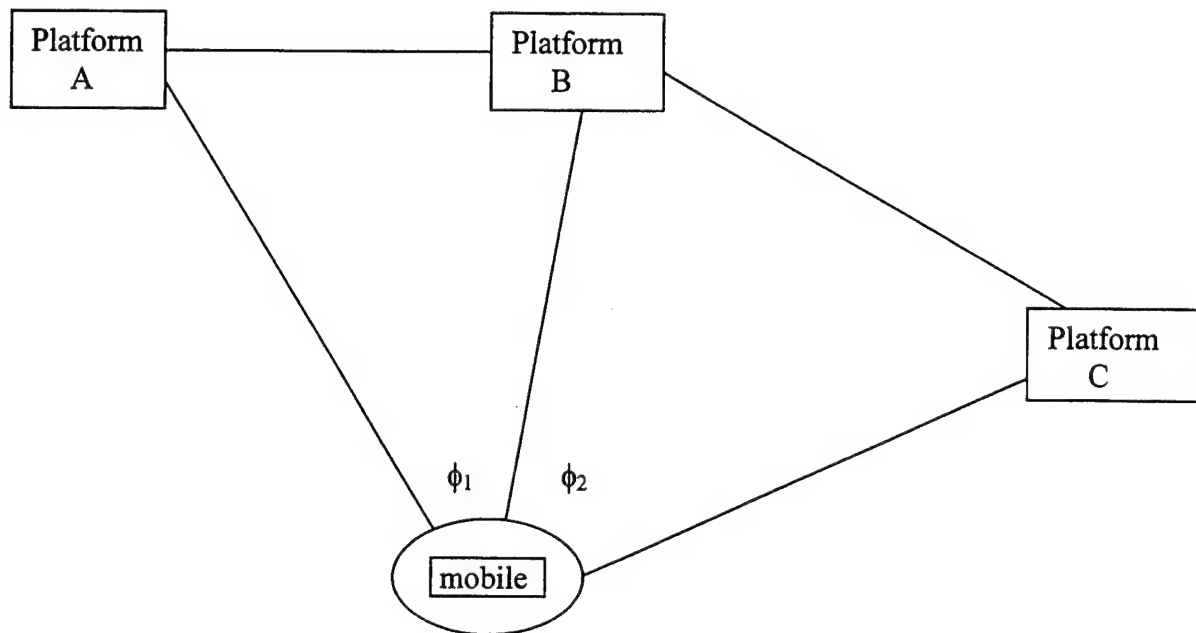


Figure 2.4: Triangulation

Another variation of the AOA method relies upon the sectoring of cells for all of its positioning information. Cell sectoring involves the use of highly directive antennas to effectively divide the cell into multiple sections. The angle of arrival can be determined at the base station by electronically steering the main lobe of an adaptive phased array antenna in the direction of the arriving mobile signal. In this case, a single platform may be sufficient for AOA positioning, although typically, two closely spaced antenna arrays are used to dither about the exact direction of the peak incoming energy to provide a higher resolution measurement. [9]

AOA measurements might provide an excellent solution for wireless transmitter localization were it not for the fact that this method requires signals coming from the mobile to the base station be from the line of sight (LOS) direction only. This is seldom



the case in cellular systems given that the operating environment is often heavily cluttered with rough terrain, tall buildings and other obstructions.

## **2. Time of Arrival (TOA)**

Since GSM is a TDMA system, its successful operation depends on the ability of all signals to arrive at the BS at the appropriate time. And since the signals arriving at the BS's originate from different distances, the time at which the signals are sent must be varied. This is accomplished by having each BS send a timing advance (TA) to each MS connected to it. The TA is the amount by which the mobile station (MS) must advance the timing of its transmission to ensure that it arrives in the correct time slot. Obviously, the TA is a measure of the propagation time, which is proportional to the distance from the BS to the MS. Hence, the location of the MS can be constrained to a circular locus centered on the BS. If the MS could somehow be forced to hand over to two more BS's, it would be possible to implement a positioning scheme based on the intersection of the three circles.

One problem with the TOA technique is that artificially forced handoffs can be made to less optimal BS's. This degrades call quality as well as reduces system capacity. Also, this method requires that all transmitters and receivers in the system have precisely synchronized clocks, since just 1 microsecond of timing error could result in a 300 meter position location error [9]. The use of the TA, which is in essence a timestamp, is a burden that most would rather not have to deal with. Furthermore, the employment of it presents another problem. Under GSM specifications, the TA is reported in units of a bit period, which equates to a locus accuracy of 554 meters. Even this considerable amount

of area will increase when multipath degradations and dilution of precision (the amount by which errors are degraded by geometry) are taken into account.

### 3. Time Difference of Arrival

The TDOA is basically an improvement upon the TOA method. The idea behind TDOA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple base station receivers, rather than the absolute arrival time. Therefore, each TDOA measurement determines that the transmitter must lie on a hyperboloid with a constant range difference between the two receivers. The equation for this range difference is given by

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2} \quad (2.1)$$

where the coordinates  $(X_i, Y_i, Z_i)$  and  $(X_j, Y_j, Z_j)$  represent the position-fixed receivers  $i$  and  $j$ , and  $x, y$ , and  $z$  represent the unknown coordinate of the target transmitter. [9]

The location of the mobile can be estimated in two dimensions from the intersection of two or more hyperboloids generated using TDOA measurements from three or more base stations. This can be extended to three dimensions if four or more TDOA measurements are used.

As in the TOA method, the TDOA requires that all fixed transmitters and receivers in the system have precisely synchronized clocks. This, however, corresponds to the timing standards already in place at cellular base station sites. Unlike the TOA measurements, TDOA measurements do not require a timestamp of the transmitted signal.

### III. POSITION LOCALIZATION USING TDOA ESTIMATION

The process of localizing the position of a cellular transmission occurs in two stages. First, an accurate estimate of the TDOA measured values must be determined from noisy signals that are received from the mobile. This involves some type of denoising technique, the most popular being wavelet denoising, which is discussed thoroughly in [10]. Generally speaking, this involves taking the wavelet transform of the received signal, thresholding the wavelet coefficients, and performing the inverse wavelet transform on the modified coefficients. Second, a location of position estimate is determined from the TDOA calculations. Both phases are very complex and subject to minor inconsistencies that can propagate into large, unacceptable errors. Thus, accurate and efficient algorithms are required for both stages of processing.

#### A. TDOA COMPUTATIONS

In order to be able to evaluate the hyperbolic range equations, Eq. (2.1), one must first estimate the range differences  $R_{ij}$ , or equivalently, the TDOA  $t_i - t_j$ . The most widely accepted method for obtaining these values is the generalized cross-correlation method. If the transmitted signal is  $s(t)$ , then the signal that arrives at one receiver,  $x(t)$ , will be delayed and corrupted by noise and is given by the equation

$$x(t) = \alpha s(t - d_i) + n_i(t), \quad 0 < \alpha < 1 \quad (3.1)$$

where  $d_i$  is the delay time from the mobile to receiver one,  $n_i(t)$  is noise, and  $\alpha$  is the gain.

Similarly, the signal that arrives at another receiver,  $y(t)$ , is given by the equation

$$y(t) = \beta s(t - d_j) + n_j(t), \quad 0 < \beta < 1 \quad (3.2)$$

where  $d_j$  is the delay time from the mobile to receiver two,  $n_j(t)$  is the noise, and  $\beta$  is the gain. The cross-correlation function between the two received signals is derived by integrating the lag product of the two signals for a sufficiently long time period,  $T$ . This function is given by

$$\hat{R}_{x,y}(\tau) = \frac{1}{T} \int_0^T x(t)y(t-\tau)dt \quad [9]. \quad (3.3)$$

This approach imposes the requirement that the receiving base stations share a precise time reference and reference signals, but does not impose any requirement on the signal transmitted by the mobile. We can improve the SNR of the TDOA estimation by increasing the integration interval,  $T$ . The maximum likelihood estimate of the TDOA is obtained from the computed cross-correlation function. This estimate is equal to the value of  $\tau$  that maximizes the cross-correlation function, Eq. (3.3).

Another method of estimating the cross correlation function, which yields the same results, is to compute the estimated cross-spectral density function. An inverse Fourier Transform of the cross-spectral density yields the estimated cross-correlation function.[9]

Prior to the cross-correlation function computation, some frequency domain processing may be used to improve the ability to distinguish the desired signal from arriving multipath components. This benefit is a result of the conduciveness of frequency domain processing to filtering techniques which are effective in reducing the effects of noise and interference on the TDOA estimate.

## **B. OBTAINING A POSITION LOCATION ESTIMATE**

After an accurate estimate of the TDOA measurement is obtained, it is then possible to determine the corresponding solution to the hyperbolic equation. This process is initiated by substituting the range difference estimate from Eq. (2.1) into the hyperbolic equation, Eq. (3.3), then solving for the Cartesian coordinates of the mobile. The solution obtained will not be a trivial one, since the range estimates will most likely be noisy or inconsistent. The solution to the hyperbolic equation is also complicated by the fact that the fixed location receivers are arranged in a non-uniform fashion. This may be accounted for by linearizing the equations through Taylor-series expansion in which only the first two terms are retained. However, this can result in significant position location errors due to geometric dilution of precision (GDOP) effects. GDOP occurs when a relatively small range of errors results in a large position location error due to a very large difference in distance between the mobile unit location on the hyperbola and the locations of the two receivers being used.

There have been several proposed solutions to reduce the above inaccuracies. One being an exact solution for the case where the number of equations equals the number of unknown coordinates. However, this solution does not account for redundant information. Other proposals include spherical interpolation, a divide-and-conquer-based solution, and more recently, a proposal, by Y. T. Chan, is a closed form solution which is valid for both close and distant sources [9]. Chan's method has been shown to be the superior of those mentioned by virtue of a lower computational complexity and higher noise threshold tolerance. In fact, Chan's method guarantees optimum performance around small TDOA noise region since it has been shown to achieve the Cramer-Rao lower bound in this region. [12]

The essence of Chan's method is to introduce an intermediate variable to the original TDOA equations, then transform the nonlinear equations relating TDOA estimates and the source position into a set of equations which are linear in the unknown parameters and the intermediate variable. A least-squares computation produces an initial solution. By exploiting the known relation between the intermediate variable and the position coordinates, a second weighted least squares computation gives the final solution for the position coordinates. [13]

### **C. DETERMINING THE ACCURACY OF POSTION LOCATION MEASUREMENT**

In an effort to measure the performance of TDOA position location systems, there are several grading criterion at one's disposal, all of which focus upon the accuracy of the

position measurement. The most obvious and most widely used measure of accuracy is the root mean square (rms) accuracy. This is defined as the rms deviation of the measured position  $(\hat{x}, \hat{y})$  about the true position  $(x, y)$ , and is given by the following equation:

$$\sigma = \sqrt{E[(\hat{x} - x)^2 + (\hat{y} - y)^2]} \quad (3.4)$$

where  $E$  is the expectation. The rms accuracy is a function of the accuracy of the raw locus measurements and the geometry of the base stations relative to the mobile. There is a limit on the achievable accuracy imposed by errors in the locus measurements. This accuracy can be further degraded by the physical geometry of the link between base stations to the mobile, referred to earlier as the GDOP. The GDOP for a 2-dimensional hyperbolic position location system is defined in [9] by:

$$GDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2}}{\sigma_R} \quad (3.5)$$

where  $\sigma_x^2$  and  $\sigma_y^2$  are the mean square position location errors in the x and y directions, respectively, and  $\sigma_R^2$  is the mean square TDOA ranging error. Ideally, it would be prudent to minimize GDOP. However, to do this would be infringing upon a very important principle in the design of mobile communication systems, where the goal is to optimize the availability of service to mobile telephone users. Thus, we can minimize the GDOP, but we will degrade the availability of service in the process. Therefore, the focus of the accuracy determination must be placed primarily on error in the locus measurement. [9]

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#### IV. METHODS TO IMPROVE TDOA ESTIMATION

Any effort to improve the TDOA estimation must focus primarily on reducing the effective noise at the receivers. Earlier research presented seven different denoising schemes designed toward this end: 1) wavelet denoising based on Donoho's method, 2) wavelet denoising using the Wo-So-Ching threshold, 3) wavelet denoising using hyperbolic shrinkage, 4) wavelet denoising using median filtering, 5) modified approximate maximum-likelihood delay estimation, 6) denoising based on the fourth order moment, and 7) a time-varying approximate maximum-likelihood technique. The results of simulation of each of these methods is shown in Figure 4.1. [10]

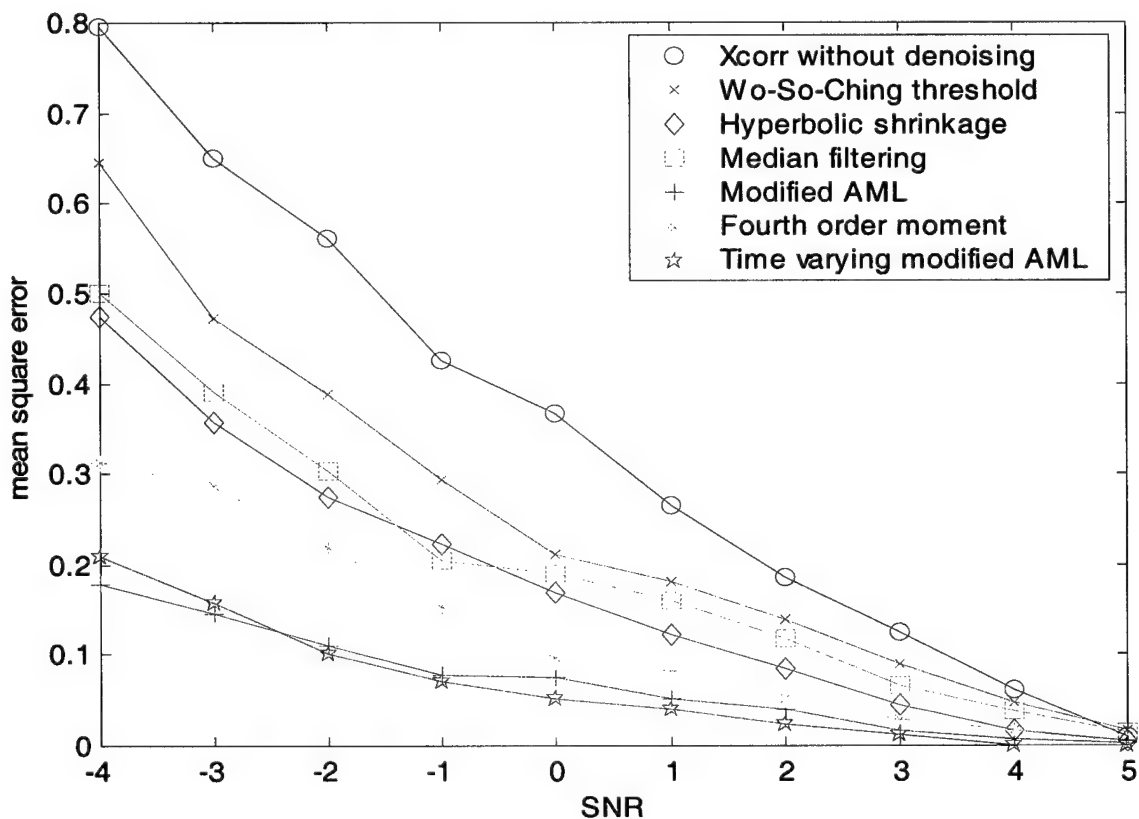


Figure 4.1: Comparison of Denoising Methods for the GSM Signal

It was shown that method 1 failed at low SNR's. Experimental results from [10] showed that method 2, while an improvement over method 1, loses its advantage with increasing carrier frequency. Additional improvements are made using methods 3 and 4, but as can be seen in Figure 4.1, the best results (lowest mean-square error) are obtained using methods 5 through 7. We will take a closer look at these last three methods.

#### A. FOURTH-ORDER MOMENT WAVELET DENOISING

Inevitably, any transmitted signal will acquire some type of additive noise before reaching the receiver. However, it is possible to estimate the frequencies of the corrupted complex sinusoidal signal. A Gaussian signal being completely characterized by its second order statistics and the odd order moments being equal to zero for a symmetric probability density function, the separation of the signal and the noise requires at least the use of the fourth-order moments [11].

To define the fourth-order moment, we first model the received signal as:

$$z(n) = x(n) + l(n) \quad (4.1)$$

where  $x(n)$  is a complex zero-mean, non-Gaussian, fourth order stationary signal and  $l(n)$  is the noise, which is a complex zero mean-Gaussian signal independent of  $x(n)$ .

The fourth-order moment is then [11]:

$$M_{4z}(j-i, k-i, l-i) \equiv E(z_i, z_j, z_k^*, z_l^*) \quad (4.2)$$

It was shown in earlier research that the fourth order moment of a detail function which contains the signal should be greater than  $3\sigma_{nd_i}^4$ , where  $\sigma_{nd_i}^4$  is the noise power at subband  $d_i$ . [10]

By using this property, the wavelet coefficients that represent noise can be eliminated while those having a signal dependency are retained. After modifying the detail functions, the denoised signal is obtained by performing an inverse wavelet transform using the modified coefficients.

## **B. MODIFIED APPROXIMATE MAXIMUM LIKELIHOOD DELAY ESTIMATION**

Critical to the task of source localization is the time delay estimation between signals received at two spatially separated sensors in the presence of noise. If we let  $s(n)$  represent the source signal,  $n_1(n)$  and  $n_2(n)$  represent the additive noises at the respective sensors, and  $D$  is the difference in arrival times at the two receivers, then the receiver outputs,  $r_1(n)$  and  $r_2(n)$ , are estimated by:

$$r_1(n) = \alpha_1 s(n) + n_1(n), \quad n = 0, 1, \dots, T-1 \quad (4.3)$$

$$r_2(n) = \alpha_2 s(n - D) + n_2(n), \quad 0 < \alpha_1, \alpha_2 < 1 \quad (4.4)$$

where  $T$  is the number of samples collected at each channel.

In the approximate maximum likelihood delay estimation, after wavelet decomposition and prior to cross-correlation, both the channel outputs are optimally weighted at different frequency bands with the use of an orthogonal wavelet transform. This weighting is done to attenuate the noise spectral components. The scaled subband

components are then combined using inverse wavelet transform to construct the Modified AML (MAML) prefiltered signal. The orthogonal wavelet transform is attractive because in addition to being computationally efficient, it does not suffer from the performance degradation due to errors that may occur in the estimation of  $D$  used in Eq. (4.4), since in practice, a highly accurate estimate of  $D$  may be difficult to achieve. [12]

The final MAML delay estimate is calculated from the location of the peak of the cross-correlation function of the two denoised signals.

### **C. TIME-VARYING MODIFIED APPROXIMATE MAXIMUM LIKELIHOOD DELAY ESTIMATION**

The time-varying MAML method, as is obvious from the name, works in much the same way as the MAML, except that it additionally accounts for the time-varying characteristics of the signal. Due to the time-varying nature of some signals, the subbands may not contain actual signal components throughout the entire segment. Therefore, the MAML method may lose some of its effectiveness when applied to segments in the presence of transitory signals. The time-varying MAML method, in essence, allows for the MAML method to be applied twice to each segment, thus approximating a time-varying gain.

## **V. SIGNAL SIMULATION AND TEST RESULTS**

### **A. SIGNAL GENERATION**

All signals used in this project for test purposes were generated using the Hewlett-Packard Advanced Design System (HP-ADS). This provided an excellent method of obtaining signals that are essentially the same as would be encountered in an actual cellular communication receiver.

#### **1. Advanced Design System**

The HP-ADS program is an invaluable tool for the engineers representing many different design aspects such as communications, digital signal processing, electronic circuits, mechanical circuits, and many others. Of course, for this project, we were particularly interested in the communications package. This package allows the user to custom design any type of communications system, run simulations of the design, and extract data collected from the simulation. Figure 5.1 shows the system used for the signal simulation. A more detailed view of each of the major components of this system can be found in Appendix [B]. Appendix [B] also provides detailed instructions for using the HP-ADS program to design and simulate a communications system.

#### **2. GSM Signal Generation**

One parameter that must be specified for the GSM signal generation is the sample time. The specifications of the GSM signal were presented in Chapter II. The HP-ADS program specifies a symbol period of 3.7037 microseconds. The filter bandwidth is 1.2

MHz. This allows us to sample at a minimum frequency of 2.4 MHz without violating the Nyquist criterion. For test purposes, we use three different sampling frequencies. As shown in Table 5.1, these are: 10.8 MHz, which corresponds to a sample time of 92.592 microseconds; 5.4 MHz, which corresponds to a sample time of 185.185 microseconds; and 2.7 MHz, which corresponds to a sample time of 370.370 microseconds.

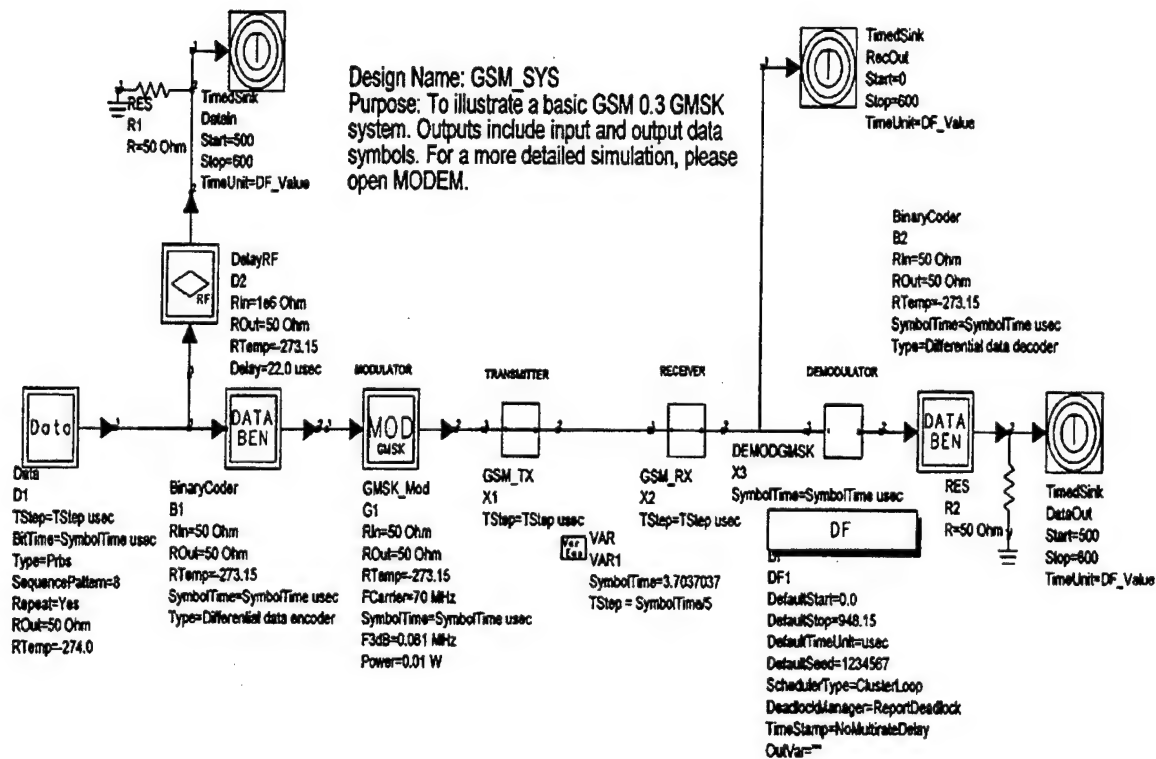


Figure 5.1: HP-ADS GSM Communications System

Samples/Symbol	Sample Time (microseconds)	Sampling Frequency (Megahertz)	Symbols/600 Samples
40	92.592	10.8	15
20	185.185	5.4	30
10	370.37	2.7	60

Table 5.1: GSM Signal Parameter Combinations

The I and Q channel outputs of each of these GSM signals are shown in Figure 5.2. One fact that is immediately evident from Figure 5.2 is that as the sampling interval increases, so does the variation in the GSM signals. The reason for this is obvious if we refer to Table 5.1. We can see that as the sample interval increases, we can expect to contain more symbols within a given number of samples. For test purposes, we use a constant number of samples (600) for all simulations. We also realize a better correlation characteristic with increasing sample time as shown in Figure 5.3. Better correlation is demonstrated by a sharper main lobe with lower sidelobes. Figure 5.3 (d) shows the correlation of the Matlab generated GSM signal presented by Aktas [10]. This figure represents the best correlation. Plots of the power spectral densities of these signals can be found in Appendix [C].

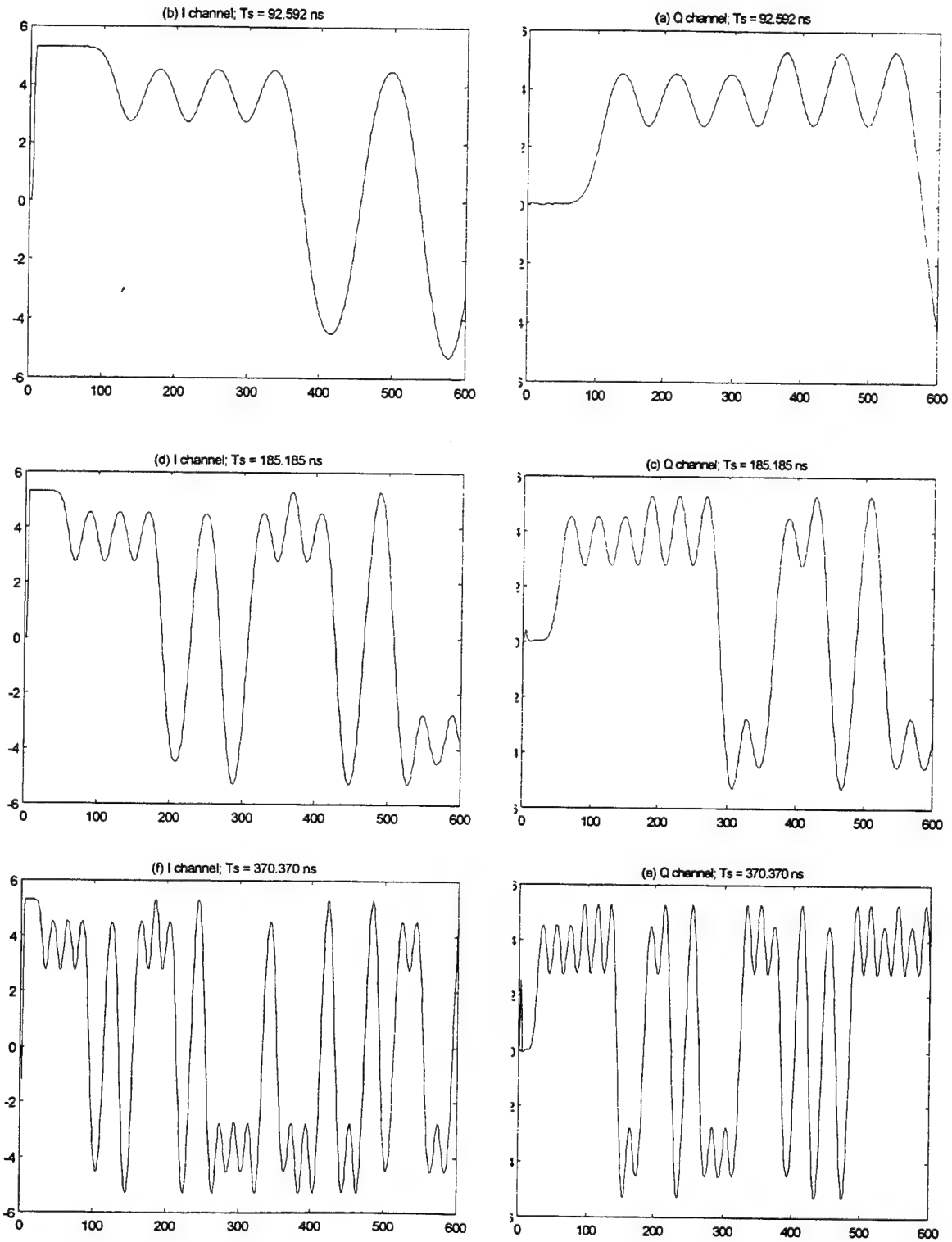


Figure 5.2: HP-ADS Produced GSM Signals



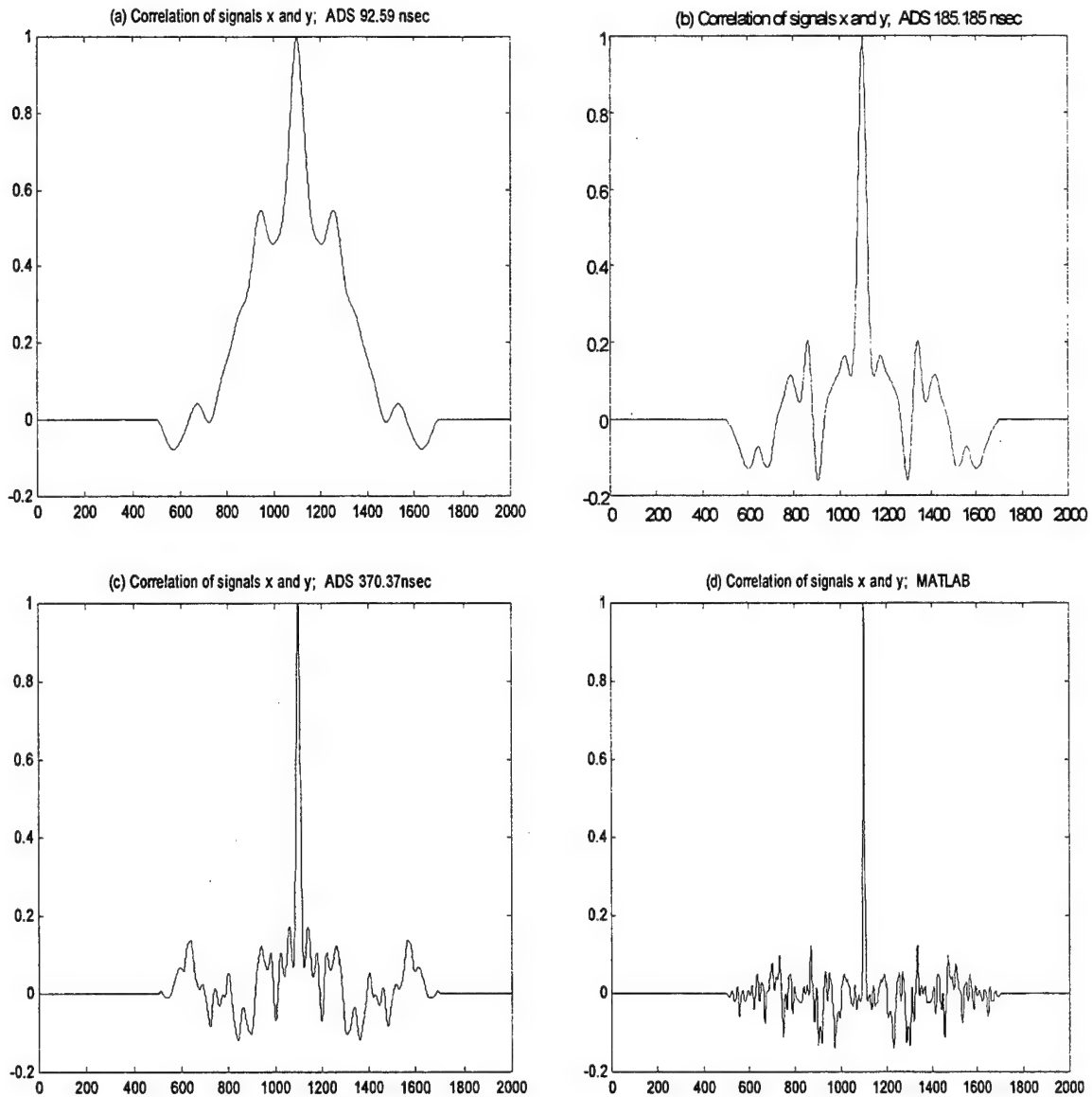


Figure 5.3: Auto-Correlation Results of Test Signals

## B. SIMULATIONS

In Chapter IV, we discussed three methods to improve the TDOA estimate. In this section, we will use these methods to test our HP-ADS generated signals and see if we are able to extract useful TDOA data. Bear in mind that our criterion for

improvement in TDOA estimation is a lower mean-squared error. Each method was tried using four different realizations for each of the three sampling times, for a total of twelve different realizations per method used. However, we will only present one set from each sample time here, as each set follows a similar trend. The remainder of the plots can be found in Appendix [D]. To simplify explanation, we shall label the data sets as follows:

- a) HP-ADS generated signal with a sample interval of 92.59 nsec.
- b) HP-ADS generated signal with a sample interval of 185.185 nsec.
- c) HP-ADS generated signal with a sample interval of 370.370 nsec.
- d) Matlab generated signal.

We will use the Matlab generated signal as our benchmark for comparison. For each method we will plot the mean-squared error against SNR's in the range of -6 dB to 20 dB. All Matlab codes used in these simulations are provided in Appendix [E]. For clarity in the following discussion, we define the terms average error and percentage improvement. Average error is calculated by adding all non-zero error values for a particular realization, and dividing that sum by the total number of the non-zero elements in that realization. Percentage improvement, as shown in the equation below, is calculated by subtracting the improved value from the original value and dividing the difference by the original value then multiplying by 100.

$$\frac{\text{original value} - \text{improved value}}{\text{original value}} \times 100\% = \text{percent improvement}$$

## 1. Fourth Order Moment

The results using this method are shown in Figure 5.4. There are two obvious trends that are noticed in this figure. We can easily see that the mean-squared error

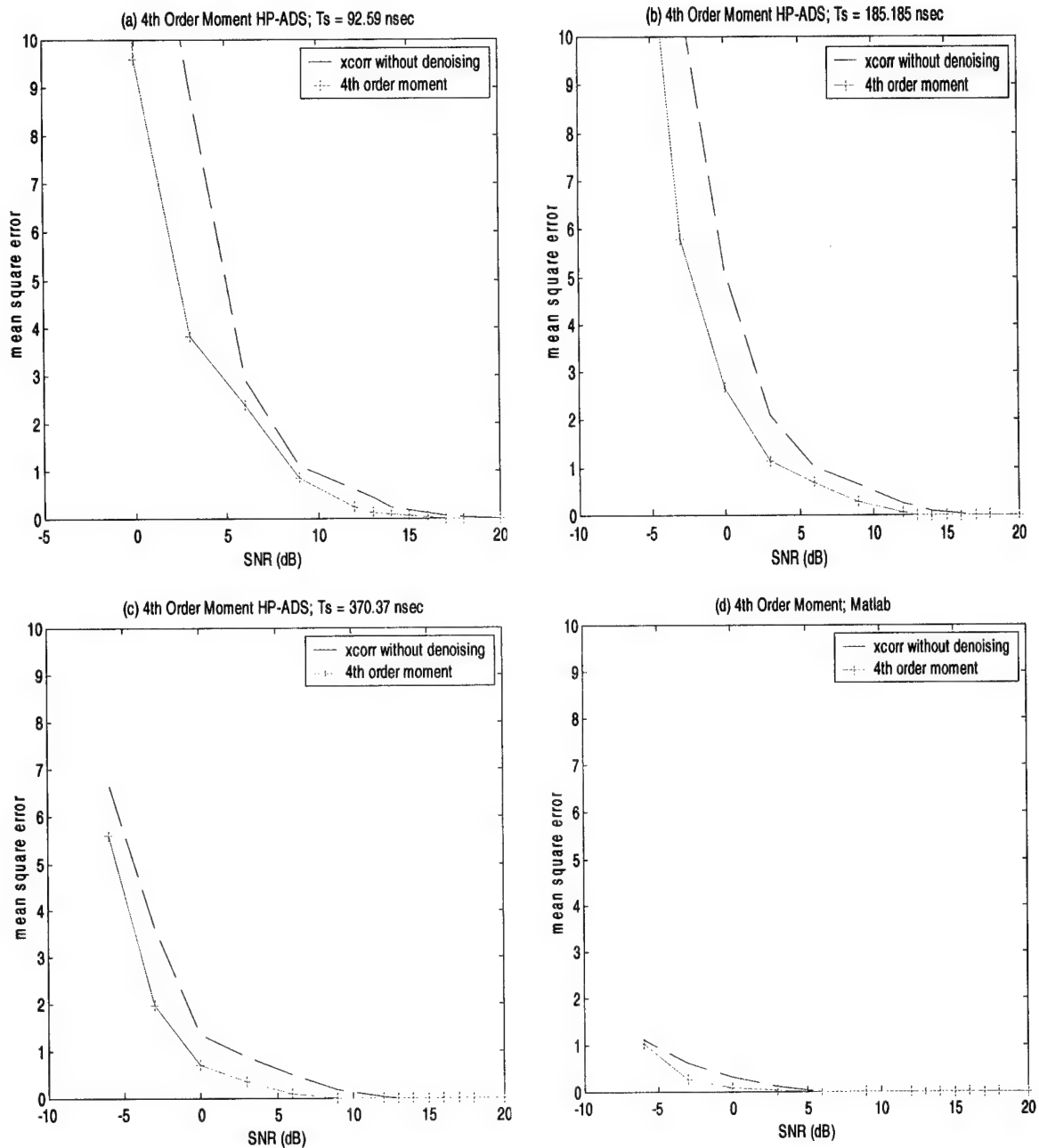


Figure 5.4: Results of Varying Sampling Interval for Fourth-Order Moment Technique

improves (decreases) as the sampling interval increases. This observation is presented numerically in Table 5.2. From this table, we can clearly see a decrease in error values as we move from left to right across each row.

In the Matlab plot (Figure 5.4 (d)), or our benchmark plot, notice that the mean-squared error is zero at 6 dB and higher SNR for the Fourth-Order Moment denoised curve. Also notice that, as expected, the denoised curve is lower than the non-denoised

S N R	Mean Squared Error							
	case (a) Sample Time = 92.59 nsec		case (b) Sample Time = 185.185 nsec		case (c) Sample Time = 370.370 nsec		case (d) Matlab Generated	
	No Denoising	Fourth- Order Denoising	No Denoising	Fourth- Order Denoising	No Denoising	Fourth- Order Denoising	No Denoising	Fourth- Order Denoising
-3	38.35	26.30	11.04	5.80	3.65	1.96	0.63	0.25
0	16.72	9.60	5.15	2.66	1.34	0.70	0.31	0.08
3	9.03	3.82	2.11	1.15	0.88	0.35	0.11	0.02
6	2.89	2.38	1.02	0.67	0.49	0.10	0	0
9	1.11	0.86	0.65	0.27	0.19	0.01	0	0
12	0.63	0.24	0.240	0.05	0.02	0	0	0
15	0.17	0.05	0.060	0	0	0	0	0
18	0.03	0.01	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0

Table 5.2: Mean-Squared Error Values at Varying SNR for the Fourth Order Moment

curve at all points. This shows that the denoising is effective in producing an improved TDOA estimate.

Using the HP-ADS data with a sampling interval of 92.59 nsec, case(a), the mean-square error at -3 dB SNR is 26.3 when fourth-order denoising is employed. This is a 31.4% improvement from the non-denoised curve. The average percentage improvement over all SNR's between -3 and 20 is 45.6%.

Using HP-ADS data with a sampling interval of 185.185 nsec, we notice an average 52.2% increase with fourth-order moment denoising. The mean-squared error is 5.68 at -3 dB, which is a 78.4% improvement over the -3 dB value of case (a).

Using HP-ADS data with a sampling interval of 370.37 nsec, case (c), we obtain even better results. The mean-squared error at -3 dB is now 1.96, which is a 65.5% improvement over case (b). The average improvement realized by using fourth-order moment denoising instead of the non-denoised method in this case is 69.0%. We now see a definite trend that as our sampling interval increases, denoising increasingly improves the mean squared error values.

In the benchmark case (d), there is a maximum mean-squared error of 0.25 at -3 dB using fourth-order denoising. The average percentage improvement of fourth-order moment denoising over non-denoising is 72.5%. We also notice that the mean-squared error is zero for all SNR above 6 dB.

The improvements we have discussed in this section can be related to the correlation function plots presented in Section 5.A. There, we saw that the correlation function plot improved with increasing sample time. Here, we state that a higher degree

of correlation of the signal components reduces the probability of error in the TDOA calculations. Thus, we achieve lower mean square error values with increasing degree of correlation of signal components.

## 2. Modified Approximate Maximum Likelihood (MAML)

The results using this method are shown in Figure 5.5. We notice a similar trend as in the fourth order moment method. We end up with lower mean squared error values

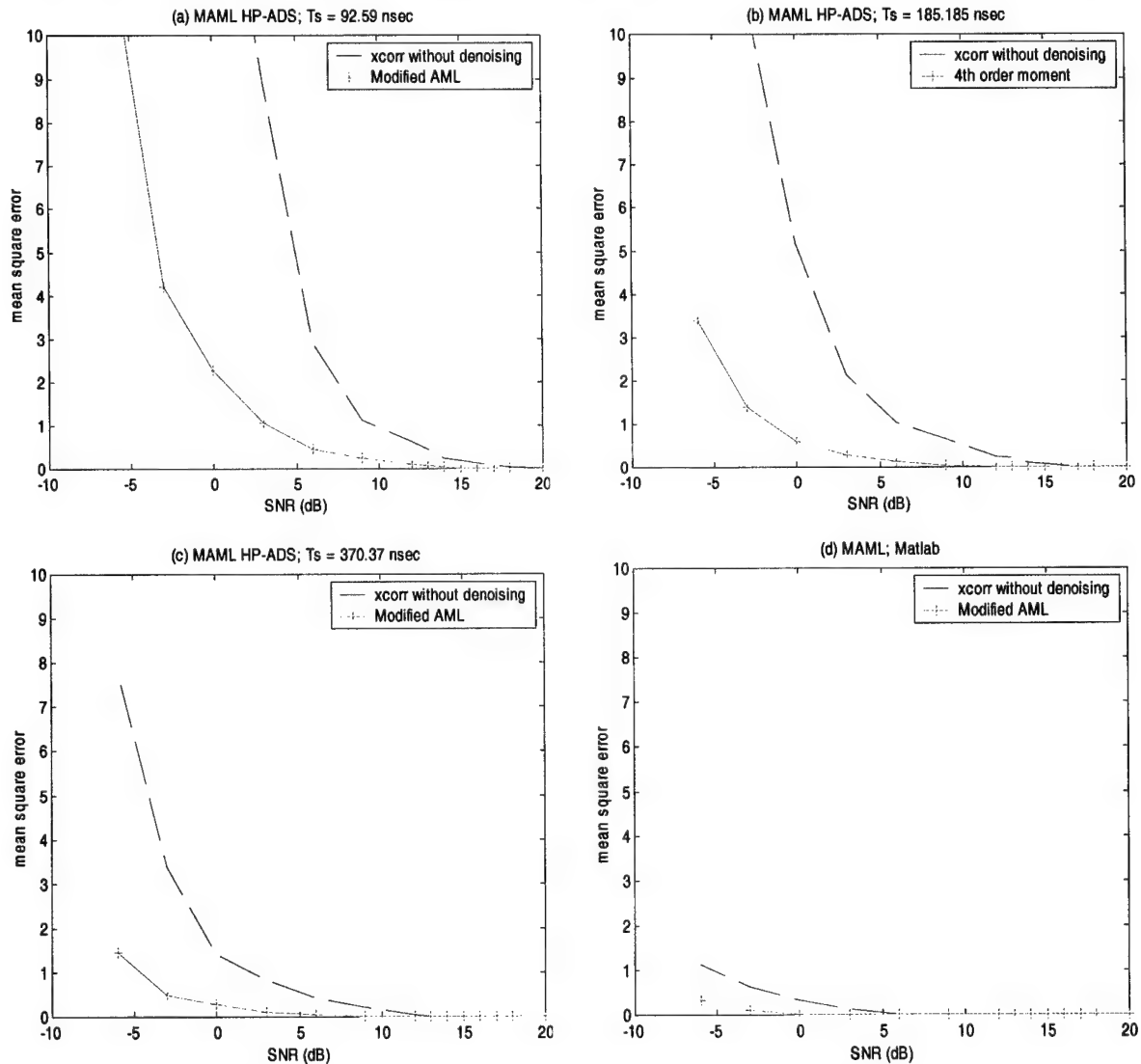


Figure 5.5: Results of Varying Sample Times for MAML Technique

as the sampling interval increases. We also notice that these mean squared error values are lower than those obtained in the fourth order moment method, as evidenced in Table 5.3.

In case (a), there is an average improvement in mean squared error of 89.6% by employing MAML denoising. Recall, from Section 5.B.1, the fourth order moment

S N R	Mean Squared Error							
	case (a) Sample Time = 92.59 nsec		case (b) Sample Time = 185.185 nsec		case (c) Sample Time = 370.370 nsec		case (d) Matlab Generated	
	No Denoising	MAML Denoising	No Denoising	MAML Denoising	No Denoising	MAML Denoising	No Denoising	MAML Denoising
-3	38.35	4.18	11.04	1.37	3.65	0.47	0.63	0.09
0	16.72	2.27	5.15	0.60	1.34	0.25	0.31	0.01
3	9.03	1.05	2.11	0.27	0.88	0.08	0.11	0
6	2.89	0.43	1.02	0.13	0.49	0.02	0	0
9	1.11	0.22	0.65	0.02	0.19	0	0	0
12	0.63	0.10	0.240	0	0.02	0	0	0
15	0.17	0	0.060	0	0	0	0	0
18	0.03	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0

Table 5.2: Mean-Squared Error Values at Varying SNR for MAML Method

denoising method produced only an average 45.6% improvement for case (a). Thus, we have proved that the MAML denoising method is, in fact, superior to the fourth order moment.

In cases (b) and (c), there is an average improvement of 89.5% and 88.8% respectively. These are in accord with the averages obtained in case (a). Thus, we have shown that through the use of the HP-ADS program, we can generate a simulated GSM signal and extract the necessary data to obtain a TDOA estimation.

### **3. Time-Varying Approximate Maximum-Likelihood (TV-MAML)**

In Figure 4.1, we saw that the time-varying MAML (TV-MAML) method produced the best results at higher SNR. The data extracted from the HP-ADS program did not produce similar results as obtained in the fourth order moment technique and the MAML method. An unsuccessful run of the TV-MAML program is shown in Figure 5.6. We can see in this figure that the MAML plot outperforms the TV-MAML plot. Furthermore, the TV-MAML plot has a non-zero mean squared error even at very high SNR. This can be explained as follows. Recall from Section 4.C., the TV-MAML requires the MAML technique be applied twice to each segment of the signal in order to reduce the probability of capturing non-signal components along with the actual signal. Recall also, all of our simulations used data sets that were 600 samples long. Therefore, the degree to which a particular data set is transitory depends upon its sample interval. Lower sampling intervals, as described in Figure 5.2, produce data sets that contain less information. Thus, the potential effectiveness of the TV-MAML is not fully realized if the signal does not contain a relatively large amount of information.



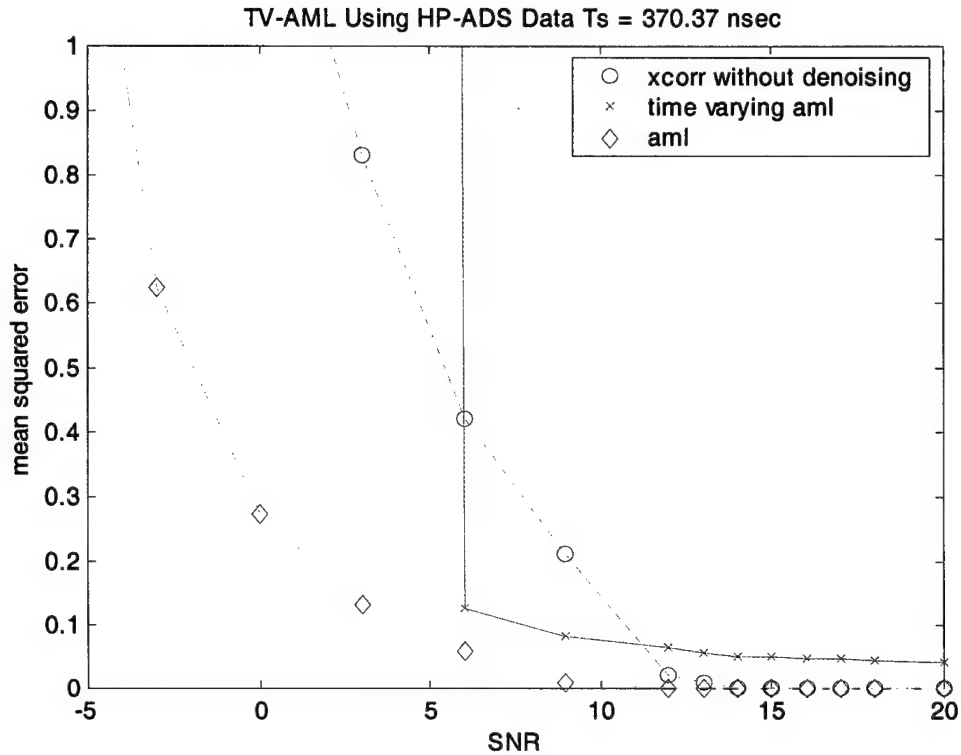


Figure 5.6: Results of Unsuccessful Run of TV-MAML Program Using Sample Interval of 370.37 nsec

In order to evaluate the effectiveness of the TV-MAML method, we must use a higher sampling interval when collecting data from the signal. Thus, we found 740 nanoseconds to be a suitable sample time. The signal is shown in Figure 5.7 along with the results from the TV-MAML program. Here, we see a definite improvement relative to Figure 5.6. The TV-MAML outperforms the MAML program at 0 dB (and lower SNR's) by an average of 18.1%. This demonstrates that the TV-MAML works better in a higher noise environment than the MAML.

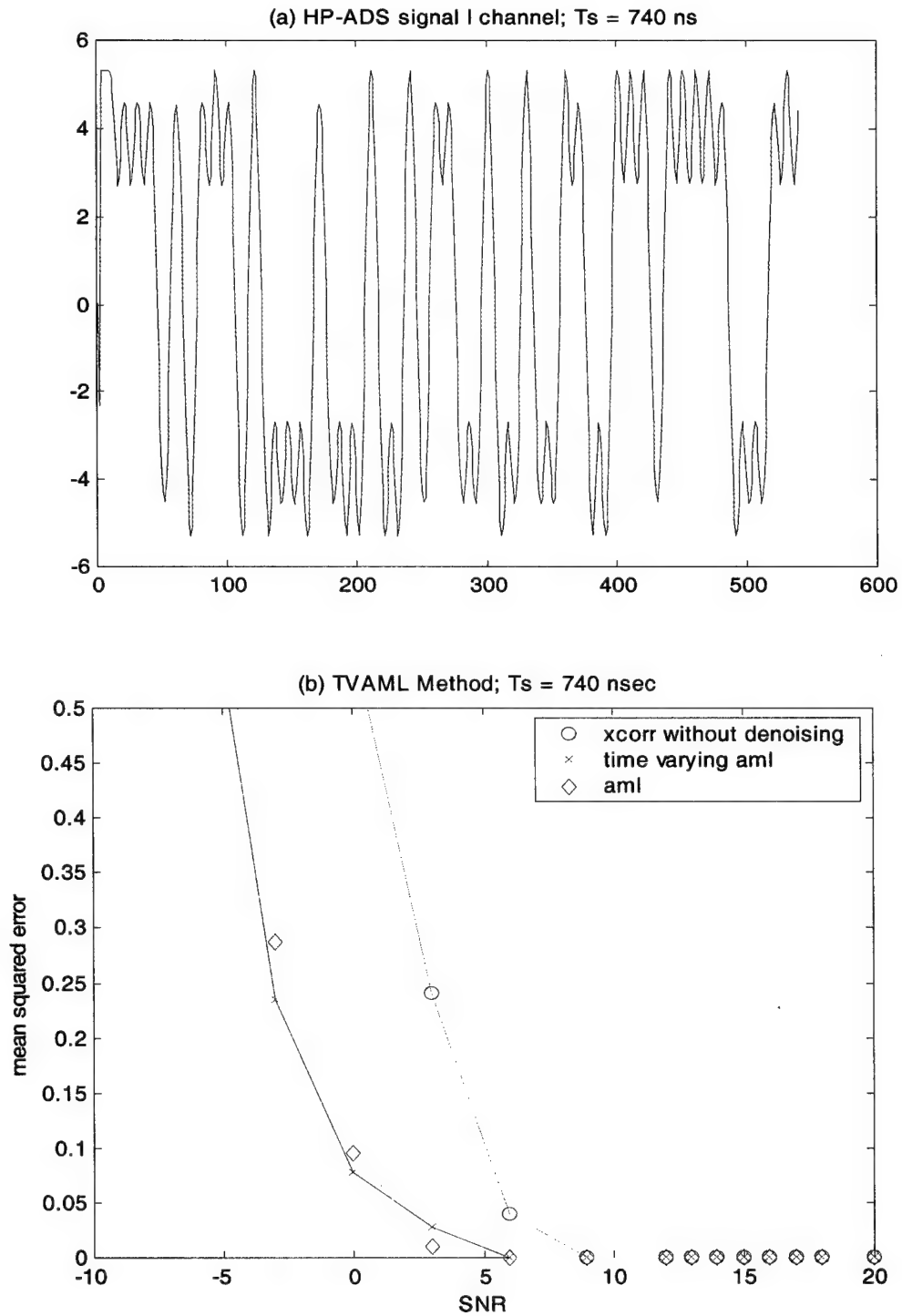


Figure 5.7: (a) HP-ADS Produced GSM I-Channel Signal With Sample Interval of 740 nsec. (b) Results of TV-MAML Using Input Signal of 740 nsec Sample Interval

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## VI. SUMMARY AND CONCLUSIONS

### A. SUMMARY

The objectives of this thesis are to simulate GSM signals and to evaluate the mean squared-error for TDOA estimation. The Hewlett-Packard Advanced Design System is a very powerful communications development tool and proved invaluable toward our objective of GSM signal generation. Appendix [F] contains a concise user's guide to the HP-ADS program for performing the tasks conducted in this thesis. We were able to manipulate this system to provide signals with desired characteristics which would later be used in the Matlab environment to determine the effectiveness of three different denoising methods. The denoising methods were presented in earlier research. These are the fourth-order moment, modified approximate maximum-likelihood, and time-varying approximate maximum-likelihood methods. We used three signal sets generated by the HP-ADS program to test the performance of each of these methods. The results of these tests agreed with the earlier research. It showed that the MAML method is the best choice except when the signal contains a relatively large amount of information, in which case the TV-MAML tends to be better.

In the process of testing the denoising techniques, we have demonstrated our ability to extract localization information from our generated GSM signals. This is manifested in the fact that we obtain relatively low mean squared error in our TDOA calculations. We also found that the error could be reduced further by increasing the interval over which samples are taken from the signal.

Although the Matlab programs provided the desired results, there were some inconsistencies to be noted. In the Matlab code for the TV-MAML, wavelet decomposition and re-composition is performed on the noise-infected input signal. At some point between the decomposition and re-composition, a dc offset is introduced as well as some slow frequency oscillation toward the end of the sequence. These issues will be addressed in subsequent work on this project.

## **B. FUTURE WORK**

In addition to providing a solution to the oscillations and DC offset described in Section 6.A., it may be possible to modify the existing Matlab code to obtain even better mean squared error values. Follow on work should also re-examine the limitations of the time-varying approximate maximum-likelihood method presented in Section 5.3. An extension to cases with different SNR's is also needed to determine the performance in a fading environment. Also, the situation where there is a weak signal in one channel and a stronger signal in the other channel should be examined. This would provide insight into the question of what ranges of SNR are reliable. Finally, an investigation into the actual position location estimation using the solution of the hyperbolic equation presented in Chapter III should be conducted.

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## APPENDIX A. USA TODAY ARTICLE ON CELLULAR 911 LEGISLATION

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### **USA TODAY** Washington

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10/26/99- Updated 05:39 PM ET

#### **Clinton signs nationwide 911 law**

WASHINGTON (AP) - President Clinton signed legislation Tuesday making 911 the official emergency number nationwide - for both regular and cellular phones.

The measure also calls for development of technology that can track mobile callers.

People with wireless phones now will be able to speed responses to highway accidents, crimes and natural disasters," Clinton said. "Getting rapid care to someone who is suffering from a heart attack or is involved in a car crash can mean the difference between life and death."

While 911 is widely used as the emergency number for traditional phones, there are 20 different codes for wireless callers across the country. The changes are aimed at cutting response times for the crews who answer 98,000 emergency calls daily from cellular phone callers.

"In my home state," said Sen. Conrad Burns, R-Mont., "three quarters of the deaths in rural areas are because the first responders couldn't get there in time."

Health care professionals joined Burns at a Capitol Hill news conference to applaud the new law.

"We have great emergency room personnel. We can do a lot for accident victims if we can find them and get them there," said Barbara Foley of the Emergency Nurses Association. "That's what this legislation helps us do."

Another provision of the act directed the Federal Communications Commission to help states develop emergency systems, including technology that can automatically locate cellular callers who have dialed 911 or been involved in an accident.

The FCC in September moved forward with plans to require that cellular 911 calls automatically provide a caller's location. Regulators want manufacturers to begin providing locator technology within two years.

Privacy advocates have raised concerns about potential abuse of the technology, which would take advantage of the Global Positioning System developed by the military.

The law signed Tuesday called on regulators to establish "appropriate privacy protection for call location information," including systems that provide automatic notification when a vehicle is involved in an accident.

It said that calls could only be tracked in nonemergency situations if the subscriber had provided written approval. "The customer must grant such authority expressly in advance of such use, disclosure or access," according to Senate documents detailing provisions of the legislation.

An estimated 700 small and rural counties have no coordinated emergency service to call - even with traditional phones. The bill would encourage private 911 providers to move into those areas by granting the same liability protections to wireless operations that now are offered to wireline emergency service systems.


Separately, the FCC took action earlier this year to increase the number of cellular calls to 911 that are successfully completed. The commission required that new analog cellular phones - not existing phones - be made with software that routes 911 calls to another carrier when a customer's own service cannot complete the call.

Calls sometimes aren't completed because a caller is in an area where his or her carrier does not have an antenna, because networks are overloaded or because buildings or geography block signals.

Digital phones, of which 18.8 million now are in use, were not covered by the new FCC rules adopted in May because such phones are more complex than their analog counterparts and there is no easy fix for the problem.

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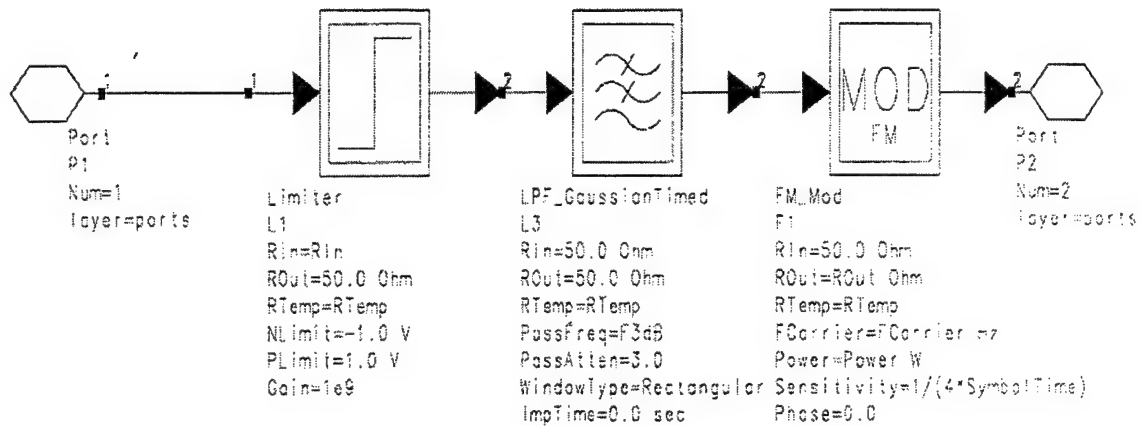
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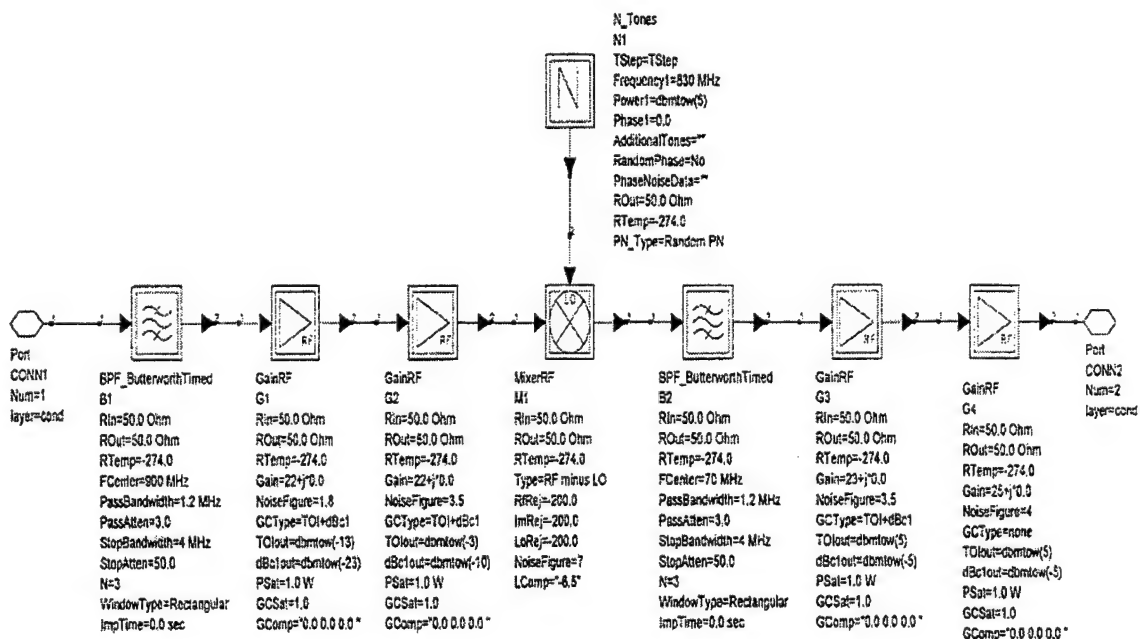


## APPENDIX B. HP-ADS GSM COMMUNICATION SYSTEM COMPONENTS

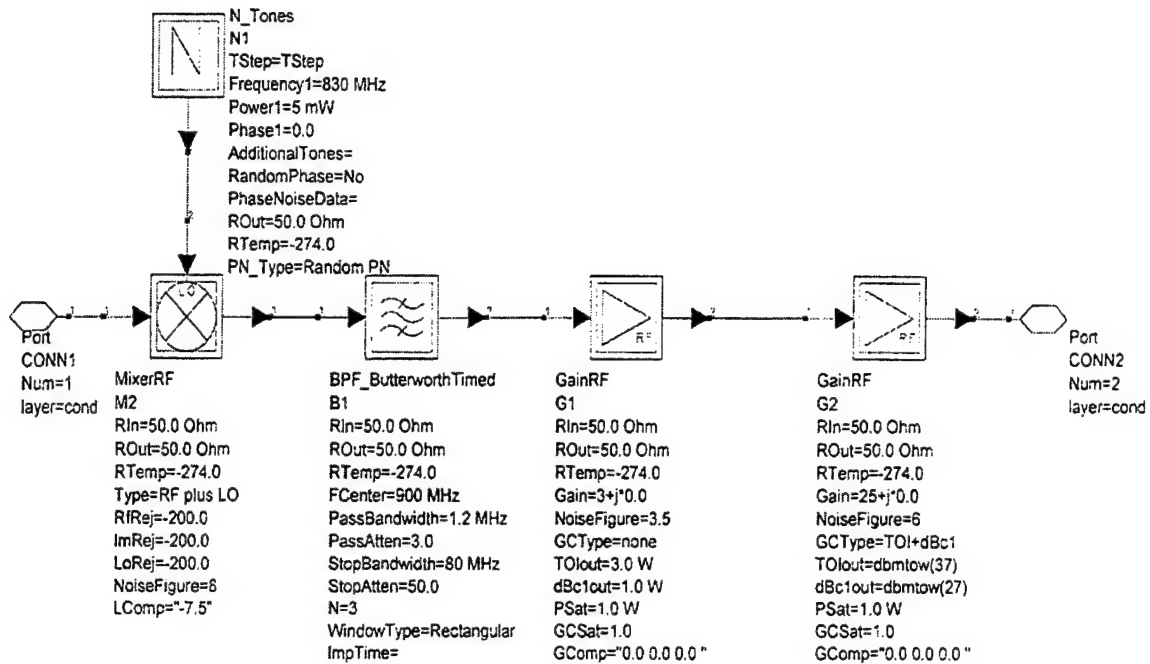
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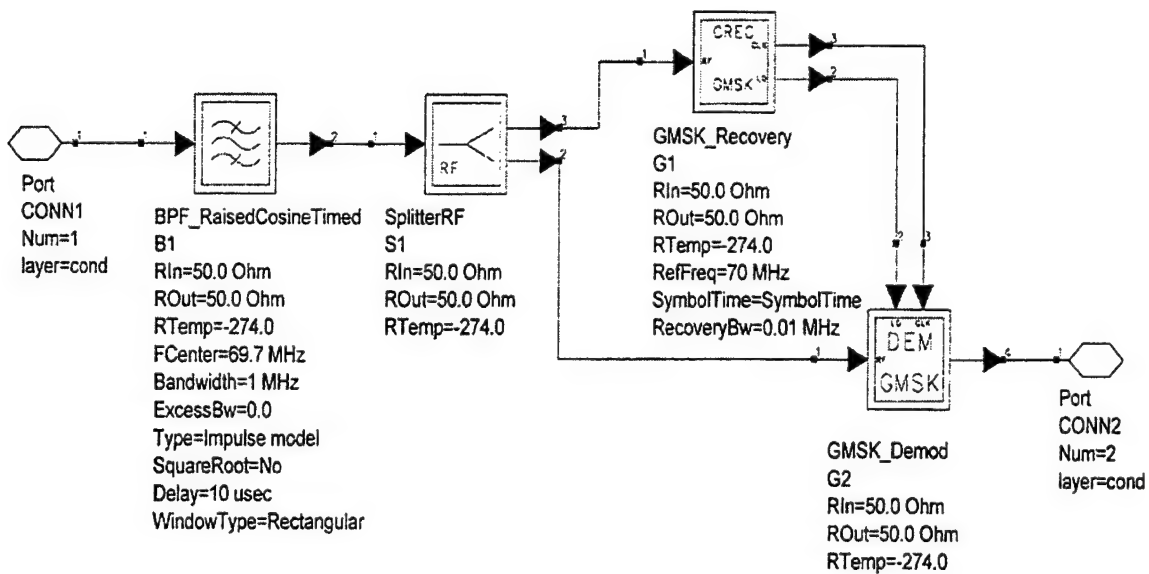
### TRANSMITTER



## RECEIVER

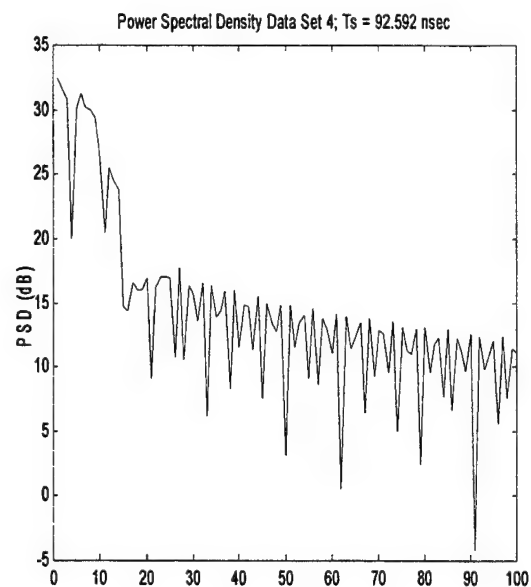
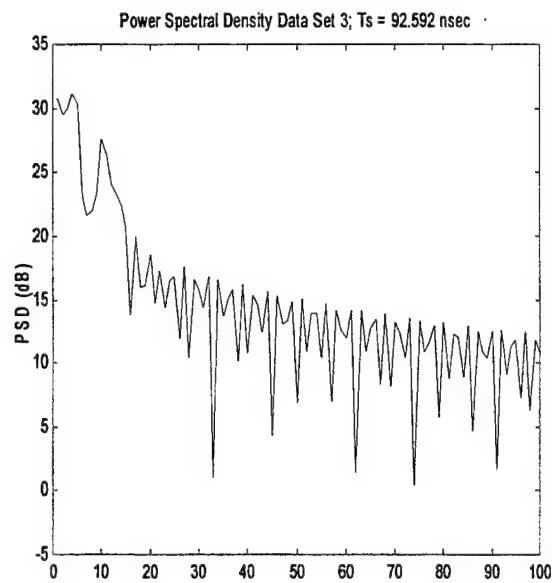
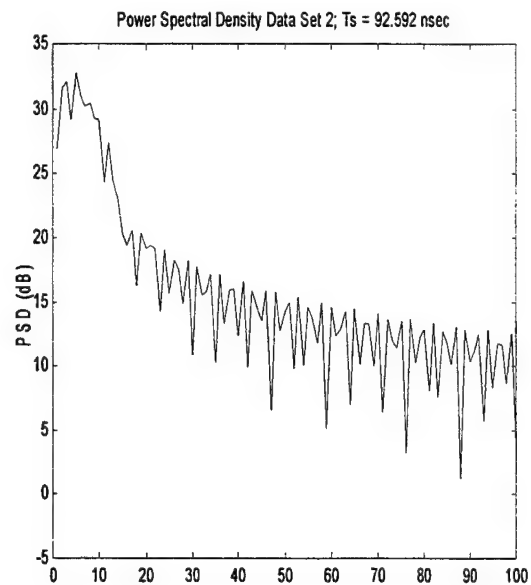
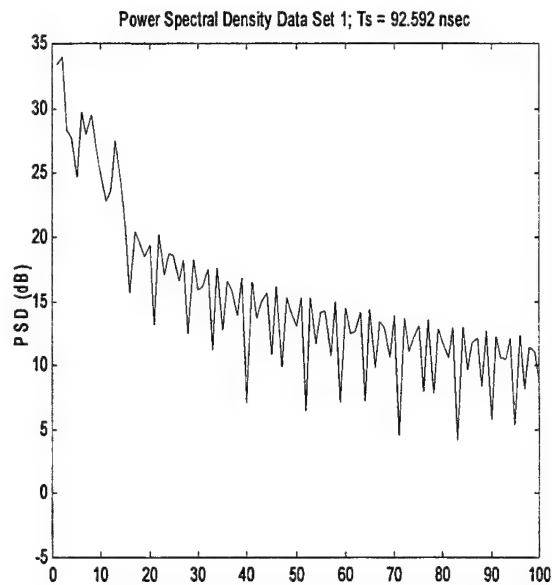


## DEMODULATOR

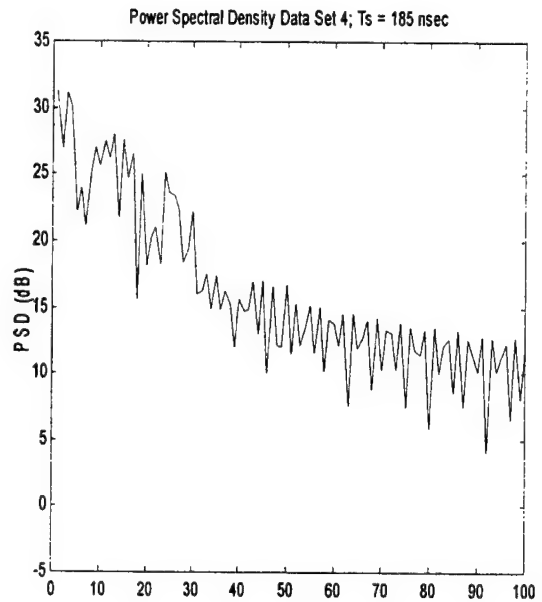
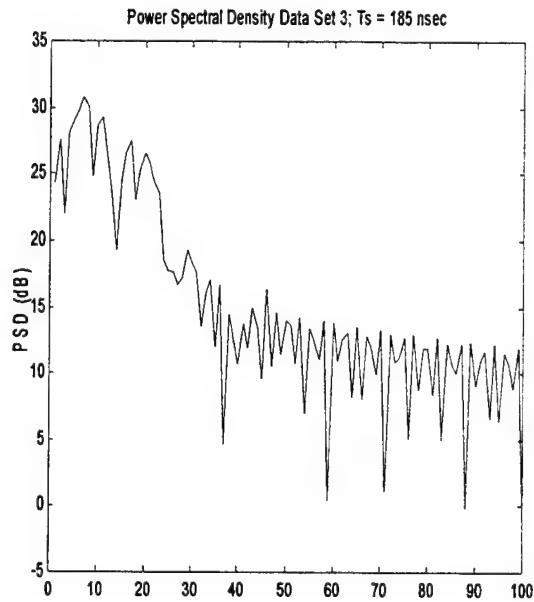
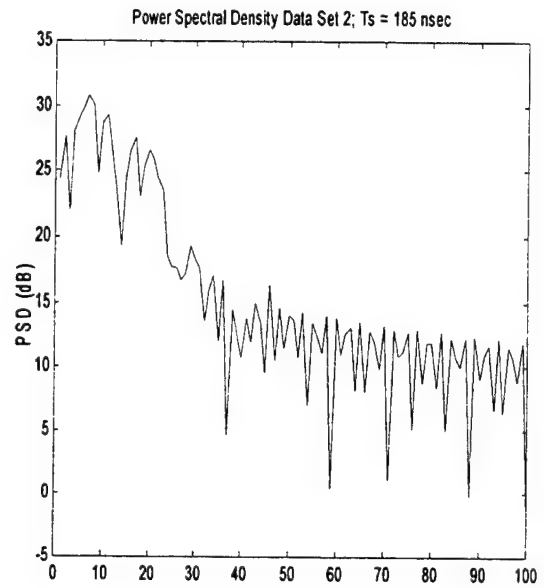
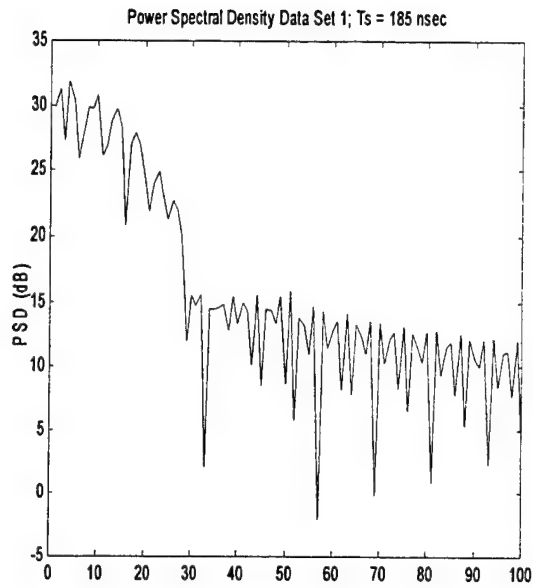


## APPENDIX C. POWER SPECTRAL DENSITIES OF GSM TEST SIGNALS

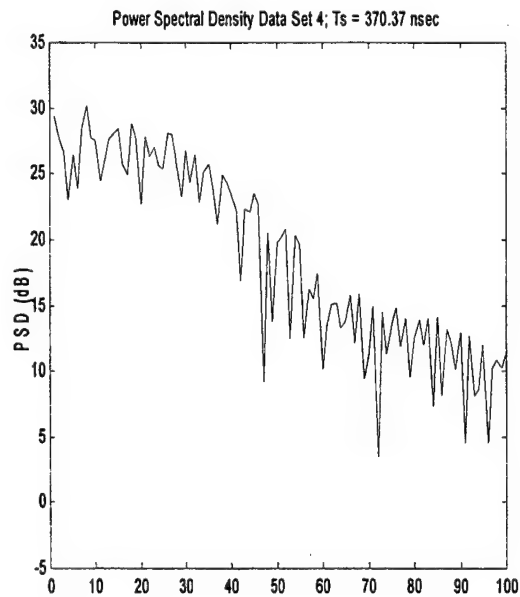
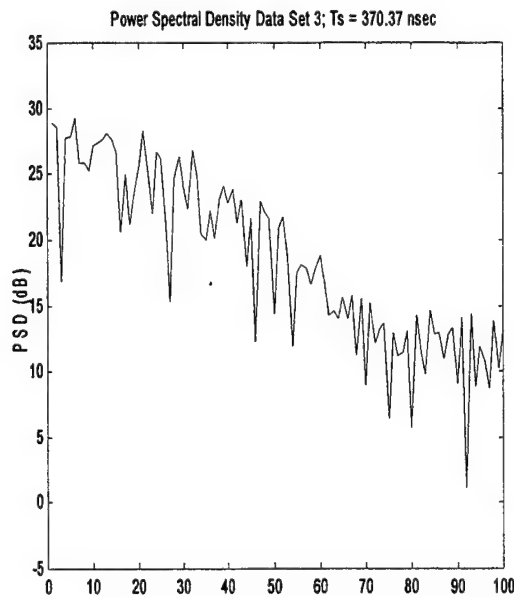
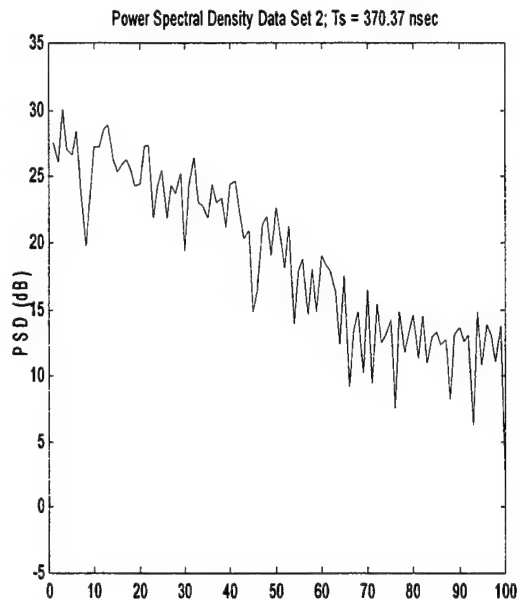
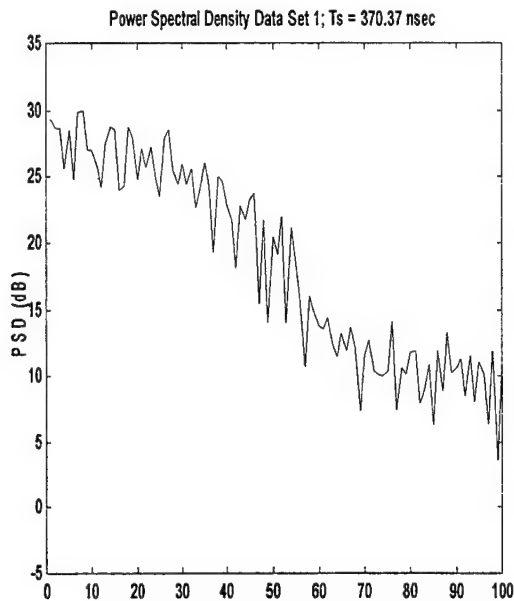
### PSD COMPARISON FOR SAMPLE TIME = 92.592 nsec



# PSD COMPARISON FOR SAMPLE TIME = 185.185 nsec



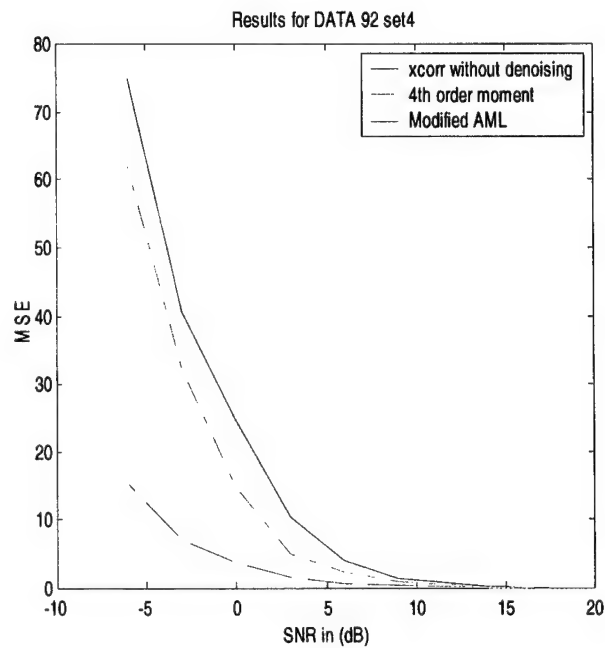
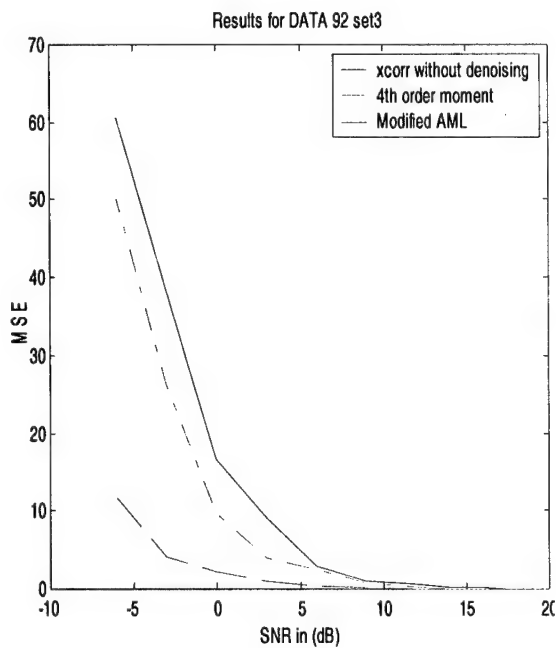
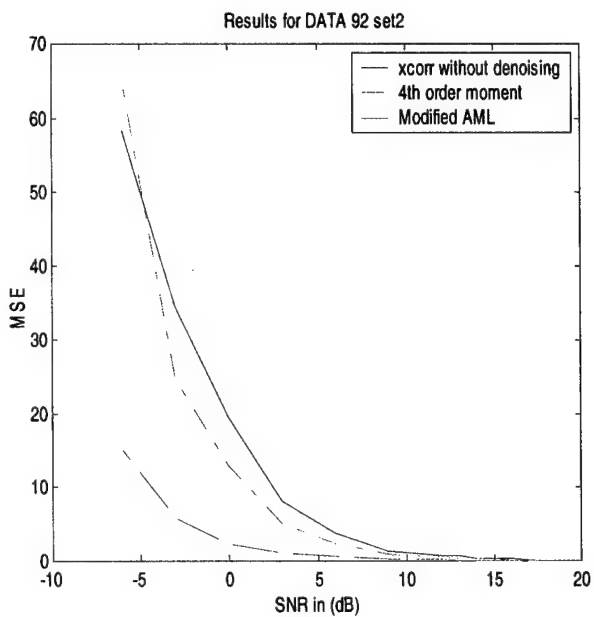
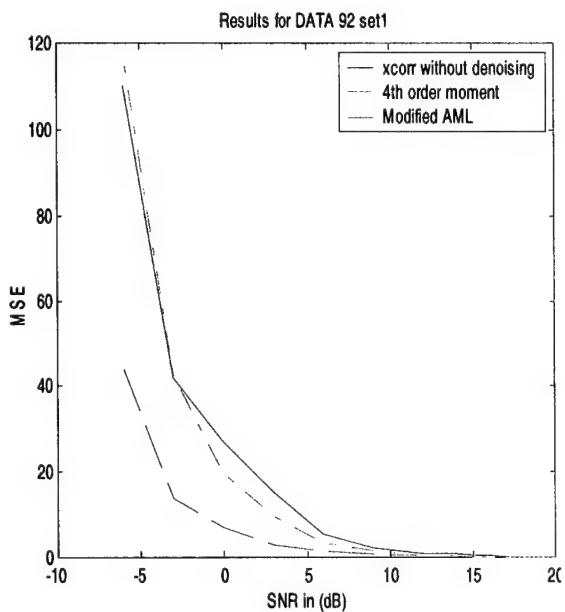
# PSD COMPARISON FOR SAMPLE TIME = 370.37 nsec



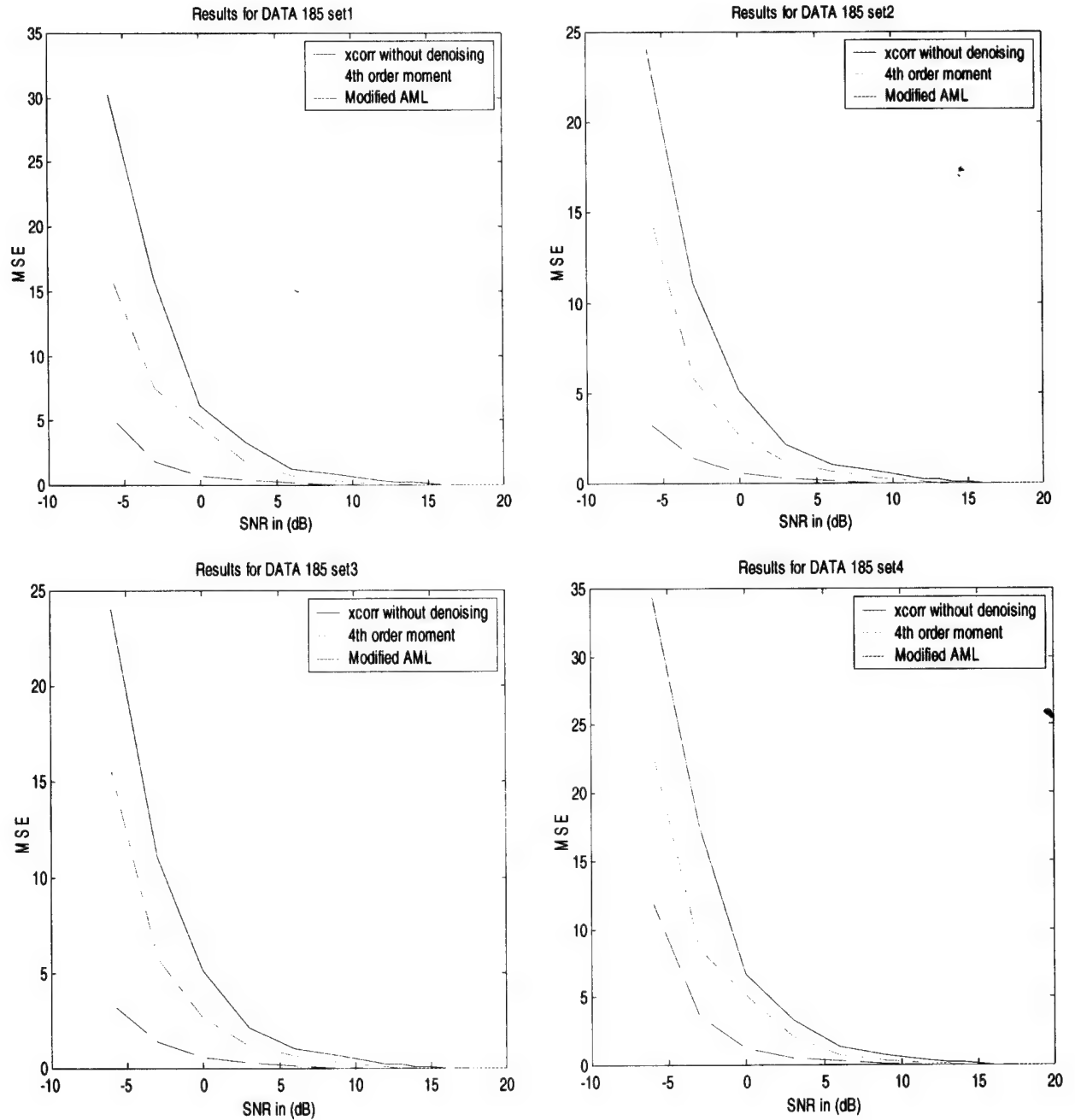


## APPENDIX D. MATLAB SIMULATIONS FOR EACH DATA SET

### FOURTH ORDER MOMENT & MAML FOR SAMPLE TIME = 92.592 nsec

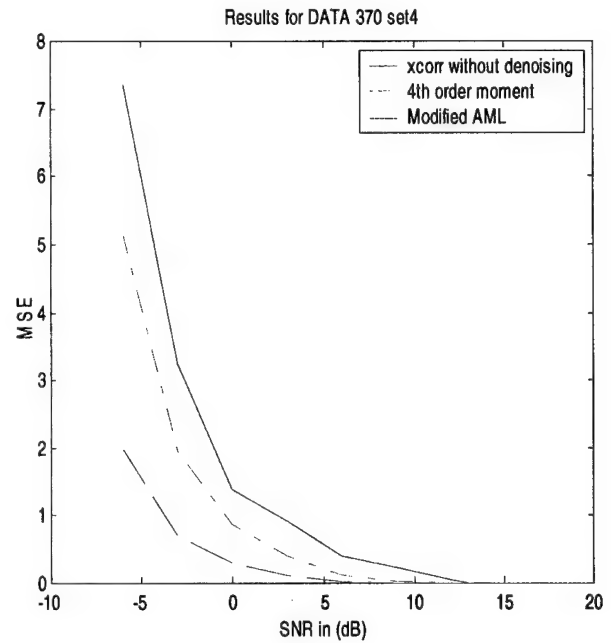
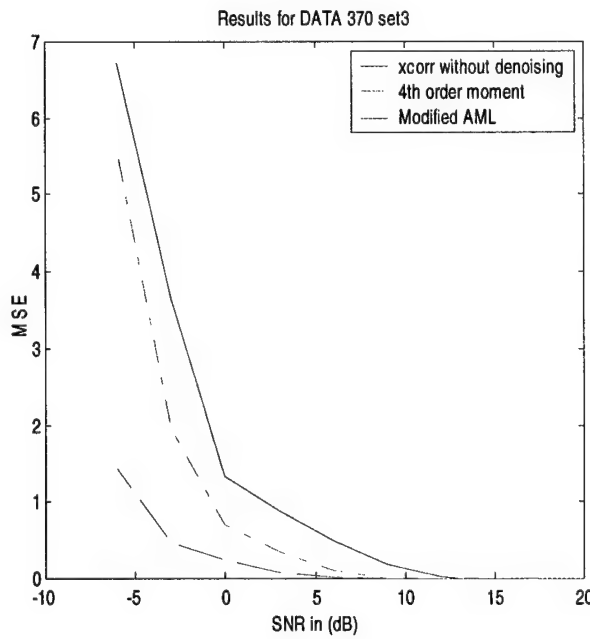
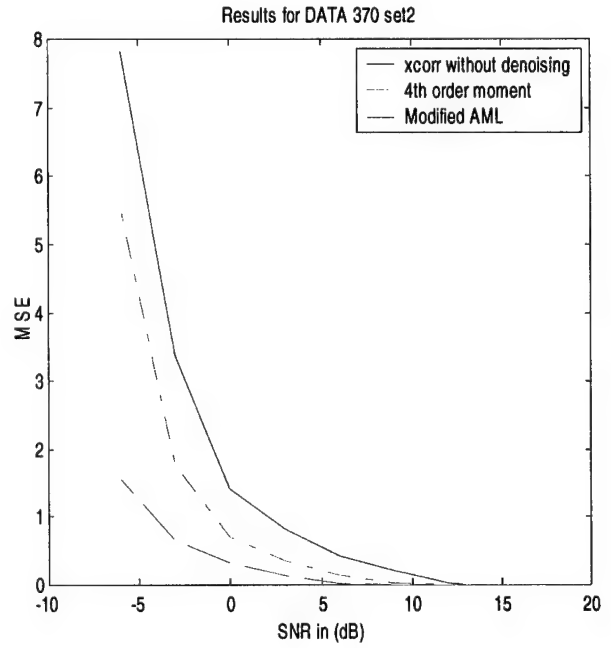
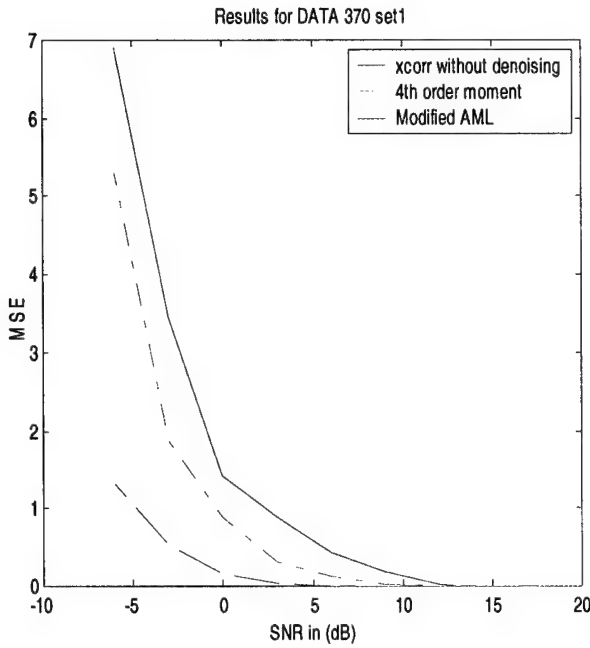


FOURTH ORDER MOMENT & MAML FOR SAMPLE TIME = 185.185 nsec





# FOURTH ORDER MOMENT & MAML FOR SAMPLE TIME = 370.37 nsec





## APPENDIX E. MATLAB CODES

### FOURTH-ORDER MOMENT DENOISING TECHNIQUE

```
% *****
% *****
% *****
% *****
% Denoise_sta: Wavelet Denosing Based on The Fourth Order
Moment
%
% SYNTAX: y=Denoise_sta(xn,yn)
%
% INPUT: xn = Received signal from first receiver
%         yn = Received signal from second receiver
%
% OUTPUT: y = Denoised signal Xn based on Yn statistics
%
% SUB_FUNC: None
% Written by Spiros Mantis
% *****
% *****
% *****
% *****

function y=Denoise_sta(xn,yn);

xyn=xcorr(xn,yn,'biased');
[sigmas b]=max(xyn);
rx=xcorr(xn,'biased');
maxx=rx(length(xn));
ry=xcorr(yn,'biased');
maxy=ry(length(yn));
sigman1=maxx-sigmas;
sigman2=maxy-sigmas;

lamdax=3.1*sigman1^2;
lamday=3.1*sigman2^2;

nx=floor(log2(length(xn)));
ny=floor(log2(length(yn)));
```

```

[cx lx]=wavedec(xn,nx,'db4');
[cy ly]=wavedec(yn,ny,'db4');

dxc=[];
for i=1:nx
    d=detcoef(cx,lx,i);
    dl=length(d);
    A=(1/dl)*sum(d.^4);

    if A<lamdax
        dc=zeros(1,dl);
    else
        dc=d;
    end

    dxc=[dc dxc];
end

a=appcoef(cx,lx,'db4',nx);
al=length(a);
A=(1/al)*sum(a.^4);

if A<lamdax
    ac=zeros(1,al);
else
    ac=a;
end

dxc=[ac dxc];

xd=waverec(dxc,lx,'db4');

y=xd;

```

```

%*****
%*****
%*****
%*****
% Modified_tez6: This is a test program for wavelet
denosing
%      based on the fourth order moment technique.
%      GSM signal is used.
%
% SYNTAX: Modified_tez6
%
% INPUT: None
%
% OUTPUT: Mean square error versus SNR
%
% SUB_FUNC: Denoise_sta.m
% Written by Spiros Mantis
%*****
%*****
%*****
%*****

clear all

%gsm_set; %Configuration variables created in memory.
% these are:
%      Tb(= 3.692e-6)
%      BT(= 0.3)
%      OSR(= 4)
%      SEED(= 931316785)
%      INIT_L(= 260)

%data=data_gen(INIT_L); % this creates a binary data
%[tx_burst,I,Q]=gsm_mod(Tb,OSR,BT,data,TRAINING);

%s=I+j*Q;
data_370_set4
s=transpose(s2);
sl=length(s);
pow=(1/sl)*sum(abs(s).^2);

K=100      % number of realizations
rand('seed',40);
f=150*rand(1,K);

```

```

delay=floor(f);
delay(1:K/2)=-delay(1:K/2); % delay is between -150 to +150

n=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
SNR=10.^(n./10);

for k=1:length(SNR)

    oran=SNR(k)
    for i=1:K

        x=zeros(1,200) s zeros(1,224)];
        y=[zeros(1,200+delay(i)) s zeros(1,224-delay(i))];

        randn('state',2*(i+j));
        noi1_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',3*(i+j));
        noi1_imag=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',4*(i+j));
        noi2_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',5*(i+j));
        noi2_imag=sqrt(pow/(2*oran))*randn(1,1024);

        noi1=noi1_real+j*noi1_imag;
        noi2=noi2_real+j*noi2_imag;

        xn=x+noi1; % x + noise
        yn=y+noi2; % y + noise

        % TDOA calculation with xcorr( without denoising)

        xy=xcorr(xn,yn); % correlation of x and y with xcorr
        [a1 b1]=max(real(xy));

        erl(i)=delay(i)-(b1-1024);

    % Fourth order moment denoise

```

```

X_real=Denoise_sta(real(xn),real(yn));
X_imag=Denoise_sta(imag(xn),imag(yn));
Y_real=Denoise_sta(real(yn),real(xn));
Y_imag=Denoise_sta(imag(yn),imag(xn));
X=X_real+j*X_imag;
Y=Y_real+j*Y_imag;
XY=xcorr(X,Y); % Correlation of X and Y (denoised)
[a2 b2]=max(real(XY));

er10(i)=delay(i)-(b2-1024);

end

error10a370set4(k)=(1/length(er10))*sum(er10.^2);
error1sta370set4(k)=(1/length(er1))*sum(er1.^2);

H10a370set4(k,:)=er10;
Hsta370set4(k,:)=er1;

end

figure(6)
k=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
plot(k,error1sta370set4(1:14),'o',k,error10a370set4(1:14),'
x',k,error1sta370set4(1:14),k,error10a370set4(1:14))
legend('xcorr without denoising','sta')
title('4TH ORDER method with cross corellation after
denoise; 100 realizations of data_370_set4')
ylabel('MSE')
xlabel('SNR')
figure(7)
plot(1:2047,xy)
title('Correlation Function of x and y signals w/noise')
figure(8)
plot(1:2047,XY)
title('Correlation Function of x and y signals without
noise')

```

```
save error10a370set4;  
save error1sta370set4;
```

```
save Hsta370set4;  
save H10a370set4;
```



## MODIFIED APPROXIMATE MAXIMUM LIKELIHOOD DENOISING

### TECHNIQUE

```
%*****
%*****
%*****
%*****
% Denoise: Approximate maximum-likelihood delay estimation
%           via orthogonal wavelet transform. In this function,
%           we assumed that noise is Gaussian noise and it has
%           a
%           flat freq response. We modify each detail function
%           by multiplying modified AML coefficient based on
%           the signal and noise powers.
%
% SYNTAX: y=aml1(xn,yn)
%
% INPUT: xn = Received signal from first receiver
%         yn = Received signal from second receiver
%
%
% OUTPUT:
%         y = Denoised signal
%
% SUB_FUNC: None
% Written by Spiros Mantis
%*****
%*****
%*****
%*****
```

```
function y=denoise(xn,yn);
```

```
xyn=xcorr(xn,yn,'biased');
[sigmas b]=max(xyn);
rx=xcorr(xn,'biased');
maxx=rx(length(xn));
ry=xcorr(yn,'biased');
maxy=ry(length(yn));
sigman1=maxx-sigmas;
sigman2=maxy-sigmas;
```

```

nx=floor(log2(length(xn)));
ny=floor(log2(length(yn)));

[cx lx]=wavedec(xn,nx,'db4');
[cy ly]=wavedec(yn,ny,'db4');

dxc=[];
for i=1:nx
    d=detcoef(cx,lx,i);
    dl=length(d);
    sigmad=(1/dl)*sum(d.^2);
    sigmasd=sigmad-sigman1;
    sigmaa(i)=(2^(nx-1))*sigmasd;
    if sigmasd<=0
        wd=0;
    else

wd=sigmasd/(sigman1*sigman2+sigmasd*(sigman1+sigman2));
        end
        dc=wd*d;
        dxc=[dc dxc];
    end

a=appcoef(cx,lx,'db4',nx);
al=length(a);
aux=sum(sigmaa);
sigmasa=((2^nx))*sigmas-aux;
if sigmasa<=0
    wa=0;
else
    wa=sigmasa/(sigman1*sigman2+sigmasa*(sigman1+sigman2));
end
ac=wa*a;
dxc=[ac dxc];

xd=waverec(dxc,lx,'db4');
y=xd;

```

```

%*****
%*****
%*****
%*****
%
% Modified_tez5: This is a test program for modified AML
technique. In this
%      program, we used GSM signal.
%
% SYNTAX: Modified_tez5
%
% INPUT: None
%
% OUTPUT: Mean square error versus SNR
%
% SUB_FUN: Denoise.m
% Written by Spiros Mantis
%*****
%*****
%*****
%*****

clear all

gsm_set;    % Configuration variables created in memory.
%these are:
            % Tb(= 3.692e-6)
            % BT(= 0.3)
            % OSR(= 4)
            % SEED(= 931316785)
            % INIT_L(= 260)

data=data_gen(INIT_L); % this creates a binary data
[tx_burst,I,Q]=gsm_mod(Tb,OSR,BT,data,TRAINING);

s=I+j*Q;
sl=length(s);
pow=(1/sl)*sum(abs(s).^2);

K=100      % number of realizations
rand('seed',40);
f=150*rand(1,K);

```

```

delay=floor(f);
delay(1:K/2)=-delay(1:K/2); % delay is between -150 to +150

n=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
SNR=10.^(n./10);

for k=1:length(SNR)

    oran=SNR(k)
    for i=1:K

        x=zeros(1,200) s zeros(1,224)];
        y=[zeros(1,200+delay(i)) s zeros(1,224-delay(i))];

        randn('state',2*(i+j));
        noi1_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',3*(i+j));
        noi1_imag=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',4*(i+j));
        noi2_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',5*(i+j));
        noi2_imag=sqrt(pow/(2*oran))*randn(1,1024);

        noi1=noi1_real+j*noi1_imag;
        noi2=noi2_real+j*noi2_imag;

        xn=x+noi1; % x + noise
        yn=y+noi2; % y + noise

        % TDOA calculation with xcorr( without denoising)

        xy=xcorr(xn,yn); % correlation of x and y with xcorr
        % (with the presence of noise)
        [a1 b1]=max(real(xy));

        erl(i)=delay(i)-(b1-1024);

        %AML

        x_real=denoise(real(xn),real(yn)); % Denoising of the
        %received signals

```

```

    y_real=denoise(real(yn),real(xn));
    x_imag=denoise(imag(xn),imag(yn));
    y_imag=denoise(imag(yn),imag(xn));

    X=x_real+j*x_imag;
    Y=y_real+j*y_imag;

    XY=xcorr(X,Y); % Correlation of X and Y (denoised)
    [a2 b2]=max(real(XY));

    er8(i)=delay(i)-(b2-1024);

end

error8a(k)=(1/length(er8))*sum(er8.^2);
error1a(k)=(1/length(er1))*sum(er1.^2);

H8a(k,:)=er8;
H1a(k,:)=er1;

end

figure(6)
k=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
plot(k,error1a(1:14),'o',k,error8a(1:14),'x',k,error1a(1:14)
),k,error8a(1:14))
legend('xcorr without denoising','aml')
title('Denoise AML method with cross corellation after
denoise; 100 realizations')
ylabel('MSE')
xlabel('SNR')
figure(7)
plot(1:2047,xy)
title('Correlation Function of x and y signals w/noise')
figure(8)
plot(1:2047,XY)
title('Correlation Function of x and y signals without
noise')

save error8a;
save error1a;

save H1a;
save H8a;

```

## TIME-VARYING MODIFIED APPROXIMATE MAXIMUM LIKELIHOOD

### DENOISING TECHNIQUE

```

%*****
%*****
%*****
%*****
% aml2: We modified the MAML technique by dividing each
%       detail function into two segments. Different
%       coefficients for each segment are computed.
%
% SYNTAX: y=aml2(xn,yn,delay)
%
% INPUT: xn = Received signal from first receiver
%        yn = Received signal from second receiver
%        delay = True TDOA between xn and yn
% OUTPUT: y = Error between true TDOA and estimated TDOA
%
% SUB_FUNC: None
% Written by Unal Aktas
%*****
%*****
%*****
%*****

```

```
function y=aml2(xn,yn,delay);
```

```

xyn=xcorr(xn,yn,'biased');
[sigmas b]=max(xyn);
rx=xcorr(xn,'biased');
maxx=rx(length(xn));
ry=xcorr(yn,'biased');
maxy=ry(length(yn));
sigman1=maxx-sigmas;
sigman2=maxy-sigmas;

nx=floor(log2(length(xn))); %10
ny=floor(log2(length(yn)));

```

```

[cx lx]=wavedec(xn,nx,'db4');%wavelet decomposition of xn
%at level 10
[cy ly]=wavedec(yn,ny,'db4');

dxc=[];
for i=1:nx
    d=detcoef(cx,lx,i); %detail coefficients at level i
    dl=length(d); %7
    Ns1=128/2^(i-1); % the length of the subblock
    if Ns1<=1 %i>=7; 1<i>10
        Ns=dl; %7
    else
        Ns=Ns1; % .25<Ns1>128
    end

    D=ceil(dl/Ns);
    if dl<Ns*D
        dm=[d zeros(1,D*Ns-dl)];
    end
    for k=1:D
        p=(k-1)*Ns+1:k*Ns;
        sigmad=(1/Ns)*sum(dm(p).^2);
        sigmasd=sigmad-sigman1;
        if sigmasd<=0
            wd=0;
        else
            wd=sigmasd/(sigman1*sigman2+sigmasd*(sigman1+sigman2));
        end
        dc(p)=wd*dm(p);
    end
    dxc=[dc(1:dl) dxc];
end

a=appcoef(cx,lx,'db4',nx);
al=length(a);
sigmaa=(1/al)*sum(a.^2);
sigmasa=sigmaa-sigman1;
if sigmasa<=0
    wa=0;
else
    wa=sigmasa/(sigman1*sigman2+sigmasa*(sigman1+sigman2));
end
ac=wa*a;
dxc=[ac dxc];

```

```

xd=waverec(dxc,lx,'db4');

dyc=[];
for i=1:ny
    dy=detcoef(cy,ly,i);
    dyl=length(dy);
    Ns1=128/2^(i-1);      % the length of the subblock
    if Ns1<=1
        Ns=dyl;
    else
        Ns=Ns1;
    end

    D=ceil(dyl/Ns);
    if dyl<Ns*D
        dmy=[dy zeros(1,D*Ns)];
    end
    for k=1:D
        p=(k-1)*Ns+1:k*Ns;
        sigmady=(1/Ns)*sum(dmy(p).^2);
        sigmasdy=sigmady-sigman1;
        if sigmasdy<=0;
            wdy=0;
        else
            wdy=sigmasdy/(sigman1*sigman2+sigmasdy*(sigman1+sigman2));
        end
        dcy(p)=wdy*dmy(p);
    end

    dyc=[dcy(1:dyl) dyc];
end

ay=appcoef(cy,ly,'db4',ny);
ayl=length(ay);
sigmaay=(1/ayl)*sum(ay.^2);
sigmasay=sigmaay-sigman1;
if sigmasay<=0
    way=0;
else
    way=sigmasay/(sigman1*sigman2+sigmasay*(sigman1+sigman2));
end
acy=way*ay;

```



```
dyc=[acy dyc];  
yd=waverec(dyc,ly,'db4');  
%[wd1 wd2 wd3 wd4 wd5 wd6 wd7 wd8 wd9 wc9]  
rxyd=xcorr(xd,yd);  
[a5 b5]=max(rxyd);  
er5=delay-(b5-1024);  
y=er5;
```

```

%*****
%*****
%*****
%*****
% tez5t : This is a test program for time varying MAML
technique.
%           In this program, GSM signal is used
%
% SYNTAX: tez5t
%
% INPUT: None
%
% OUTPUT: Mean square error versus SNR
%
% SUB_FUNC: aml2.m
% Written by Unal Aktas
%*****
%*****
%*****
%*****

clear all

gsm_set; % Configuration variables created in memory,
these are:
        % Tb(= 3.692e-6)
        % BT(= 0.3)
        % OSR(= 4)
        % SEED(= 931316785)
        % INIT_L(= 260)

data=data_gen(INIT_L); % this creates a binary data
[tx_burst,I,Q]=gsm_mod(Tb,OSR,BT,data,TRAINING);

%s=I+j*Q;
data_740_set1
s=transpose(s2)
sl=length(s2);
pow=(1/sl)*sum(abs(s).^2);

K=100 % number of realizations
rand('seed',40);

```

```

f=150*rand(1,K);
delay=floor(f);
delay(1:K/2)=-delay(1:K/2); % delay is between -150 to
+150

n=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
SNR=10.^(n./10);

for k=1:length(SNR)

    oran=SNR(k)
    for i=1:K

        x=zeros(1,259) s zeros(1,224)];
        y=[zeros(1,259+delay(i)) s zeros(1,224-delay(i))];

        randn('state',2*(i+j));
        noi1_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',3*(i+j));
        noi1_imag=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',4*(i+j));
        noi2_real=sqrt(pow/(2*oran))*randn(1,1024);

        randn('state',5*(i+j));
        noi2_imag=sqrt(pow/(2*oran))*randn(1,1024);

        noi1=noi1_real+j*noi1_imag;
        noi2=noi2_real+j*noi2_imag;

        xn=x+noi1; % x + noise
        yn=y+noi2; % y + noise

        % TDOA calculation with xcorr( without denoising)

        xy=xcorr(xn,yn); % correlation of x and y with xcorr
        [a1 b1]=max(real(xy));

        erl(i)=delay(i)-(b1-1024);

    %AML

```

```

    e1=aml2(real(xn),real(yn),delay(i));
    e2=aml2(imag(xn),imag(yn),delay(i));

    e1a=aml1(real(xn),real(yn),delay(i));
    e2a=aml1(imag(xn),imag(yn),delay(i));

    er8(i)=(e1+e2)/2;

    er8a(i)=(e1a+e2a)/2;

end

error8t(k)=(1/length(er8))*sum(er8.^2);
error1a(k)=(1/length(er1))*sum(er1.^2);

error8a(k)=(1/length(er8a))*sum(er8a.^2);

H8t(k,:)=er8;
H1a(k,:)=er1;

end
%load error8a

figure(6)
k=[20 18 17 16 15 14 13 12 9 6 3 0 -3 -6];
plot(k,error1a(1:14),'o',k,error8t(1:14),'x',k,error8a(1:14)
),'d',...
    k,error1a(1:14),k,error8t(1:14),k,error8a(1:14))

legend('xcorr without denoising','time varying aml','aml')
title('TVAML Method ADS input data; Ts = 740nsec Set#1; 100
realizations')
figure(7)
plot(1:541,real(s2))
title('ADS signal (s) real component; 740ns')

save error8t;
save error1a;

save H1a;
save H8t;

```

## APPENDIX F. GUIDE FOR USING GSM SIMULATION IN HEWLETT- PACKARD ADVANCED DESIGN SYSTEM

### STEP 1: Start Program

If there is no icon on startup window:  
Start => Programs => HP-ADS => ADS

### STEP 2: Open GSM Example Project

From ADS (main) window:  
File => Example Project => Com\_Sys => gsm\_prj => ok => wait a few seconds  
for windows to pop up. (two windows come up: GSM\_SYS Schematic:2 and MODEM  
Schematic:1. The Modem Schematic is for a more detailed simulation. I have been primarily  
working with the GSM\_SYS schematic.) DO NOT MAKE ANY CHANGES TO EITHER OF  
THESE FILES!!!! Any changes will be saved in the system and they will remain there for future  
users of the program. Save to your H: drive or other drive of your choice and make changes there.

### STEP 3: Modifying the system

The options here are unbounded. You can experiment with all the different components in the  
Component Library. But for now, we just want to know how to get data out of this system.  
This is done by placing 'data sinks' in the desired locations.

Go to the common component box at the top of the schematic window and click the  
arrow. This will show all the different components available. =>

For data extraction, you want to use 'Sinks.' From there you can find the appropriate  
'sink' for your data. (Timed and Spect. Analyzer are the most commonly used)=>

Click once on the sink of your choice =>

Move the cursor into the schematic area and place the sink in the desired position by left-  
clicking when you have it in a clear spot. =>

End the command by using the right-click button on the mouse then click 'end  
command' or just hit the escape key. =>

Use wire to connect it to the system. (there is a wire button on the third row of toolbar, or  
you can go to the component button at the top) =>

Notice the name of the sink. (this is listed under the device type) This is important,  
because you will need to recall this name when you want to plot or export the data. You  
can change the name by clicking once on it and then typing the new name right there in  
the same spot.

#### **STEP 4: Simulations**

After you have your desired system configuration, are ready to simulate the system:  
Simulate(on top toolbar) => simulate => wait for "simulation finished" in summary window. The simulation is now complete and you can extract your data.

#### **STEP 5: Displaying Data**

Window(on top toolbar) => New Data Display => wait for data display window

To see an x-y plot:

Click once on the "plot" icon => move cursor into white area of display(a box appears), position the box and left-click. => choose what data you want to plot. => ok => your plot appears in the data display window.

To see data:

Click once on the "123456" icon => follow the same procedure as above.

#### **STEP 6: Extracting and Exporting Data**

I haven't figured out how to export the plots but here is how to extract the data:

In the schematic window: click on "start the instrument server" button(third button third row of toolbar) => Click the following:

Read/Write: Write

Write to: File

File Format: Citifile =>

Use the browse button to choose a directory and file name. =>

Choose desired data from Datasets box. =>

Click 'write to file' button. => your data is now saved in the specified directory.

You will have to use wordpad or notepad to view this data. Then you will have to sort through all the data given to get to the specific data. This may be annoying, but rest assured the data you want is in there somewhere!!

#### **STEP 7: Importing your ADS data into Matlab**

After you have located your data in wordpad you can cut and paste from there into Matlab.

If you want to know how many data points you have it is best to use the Matlab Editor/Debugger (unless you have a few hours to spend counting).

- Make the data into a vector in Matlab and use the size command to determine the length.
- Using this method you can cut it down to the right size.

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5. Professor Ralph Hippenstiel, Code EC/Hi.....3  
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6. Professor Tri Ha, Code EC/Ha.....1  
Department of Electrical and Computer Engineering  
Naval Postgraduate School  
Monterey, CA 93943-5121
7. LT Timothy N. Haney.....1  
221 Henrietta Ct.  
San Diego, CA 92114